

# FINAL REPORT

## Scalable Deployment of Advanced Building Energy Management Systems

ESTCP Project EW-201015

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Veronica Adetola  
Sunil Ahuja  
Trevor Bailey  
Bing Dong  
Taimoor Khawaja  
Dong Luo  
Zheng O'Neill  
Madhusudana Shashanka  
**United Technologies Research Center**

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## **Acronyms**

aBEMS: Advanced Building Energy Management System

AC: Alternating Current

AEC: Architectural, Engineering, Construction

AHU: Air Handling Unit

API: Application Programming Interface

ANSI: American National Standards Institute

ASHRAE: American Society of Heating, Refrigerating, and Air-Conditioning Engineers

BACnet: Building Automation and Control Networks

BDAS: Building Data Acquisition System

BEM: Building Energy Modeling

BIM: Building Information Modeling

BIMTB: Building Information Model Test Bed

BLCC: Building Life-Cycle Cost

BMS: Building Management System

C: Capacity

CBECS: Commercial Buildings Energy Consumption Survey

CCV: Cooling Coil Valve

CFM: Cubic Feet per Minute

CFR: Code of Federal Regulations

CHW: Chilled Water

CO<sub>2</sub>: Carbon Dioxide

COV: Change of Value

COTs: Commercial Off-the-shelf

CT: Current Transducer

DAQ: Data Acquisition

DB: Database

DC: Direct Current

DEM: Digital Energy Monitor

DDC: Direct Digital Control

DFSS: Duct Free Split System  
DoD: Department of Defense  
eHMI: Energy Human Machine Interface  
EIS: Energy Information Systems  
EKF: Extended Kalman Filter  
ESTCP: Environmental Security Technology Certification Program  
FDD: Fault Detection and Diagnosis  
FEMP: Federal Energy Management Program  
GB: Gigabyte  
GHz: Gigahertz  
GPM: Gallon per Minute  
HVAC: Heating, Ventilation and Air Conditioning  
HW: Hot Water  
iBED Viz: Integrated Buildings Energy and Diagnostics Visualization  
IFC: Industry Foundation Classes  
IPMVP: International Performance and Measurement Verification Protocol  
ISO: International Standards Organization  
KF: Kalman Filter  
MVD: Model View Definition  
NIST: National Institute of Standards and Technology  
NAVFAC: Naval Facilities Engineering Command  
NOAA: National Oceanic and Atmospheric Administration  
OSD: Office of the Secretary of Defense  
OAT: Outside Air Temperature  
PACRAT: Performance and Continuous Re-Commissioning Analysis Tool  
PC: Personal Computer  
PI: Principal Investigator  
PLC: Programmable Logic Controllers  
POC: Point of Contact  
R: Resistance  
RH: Relative Humidity

ROM: Reduced-Order Model

SCADA: Supervisory Control and Data Acquisition

SERDP: Strategic Environmental Research and Development Program

SIR: Savings to Investment Ratio

SQL: Structured Query Language

TMY: Typical Meteorological Year

UPS: Uninterruptible Power Supply

U.S.: United States

UTRC: United Technologies Research Center

V: Volts

VAV: Variable Air Volume

VFD: Variable Frequency Drive



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## **EXECUTIVE SUMMARY**

### **OBJECTIVES OF THE DEMONSTRATION**

The United Technologies Research Center (UTRC)<sup>1</sup>, with the sponsorship from DoD ESTCP program, has performed a demonstration of an advanced Building Energy Management System (aBEMS) that employs advanced methods of whole-building performance monitoring combined with statistical learning methods and data analysis to enable identification of both gradual and discrete performance erosion and faults. The specific technical objectives of the demonstration project were: 1) to demonstrate 10% building energy savings by providing the facility engineers with actionable energy fault information to identify and correct poor system performance, and 2) to demonstrate an additional 10% energy savings by identifying alternative energy system operation strategies that improve building energy performance. The demonstrated technology is targeted at commercial buildings that use building energy management systems. The demonstration was conducted in a drill hall/office building (Building 7230) and a large barracks facility (Building 7113/7114) at Naval Station Great Lakes. At Great Lakes, greater than 20% savings were demonstrated for building energy consumption by improving facility manager decision support to diagnose energy faults and prioritize alternative, energy efficient operation strategies.

### **TECHNOLOGY DESCRIPTION**

The advanced building energy management system assimilated data from multiple sources including blueprints, reduced-order models (ROM) and measurements, and employed probabilistic graphical models and other advanced statistical learning algorithms to identify patterns of anomalies. The results were presented graphically in a manner understandable to a facilities manager. The system incorporated learning algorithms and simplified reduced-order simulation models to circumvent the need to manually construct and maintain a detailed building energy simulation model. This detailed building model is required for the existing technology (demonstrated in ESTCP project SI-0929) and represents a practical barrier to a broad scalable application. The facility Building Management System (BMS) was extended to incorporate the energy diagnostics and analysis algorithms, producing systematic identification of alternative, energy efficient HVAC operation strategies. The scalability of the solution has also been demonstrated by applying 1) load estimation techniques and reduced-order models for the building and HVAC systems, reducing the need for constructing specific, detailed models for each building, and 2) probabilistic graphic models for energy diagnostics, as the graphic structure does not have to be learned for similar equipment and systems every time.

### **DEMONSTRATION RESULTS**

The performance objectives were met during the demonstration as shown in Table 1.1. The overall performance evaluation for the aBEMS is summarized as follows:

- Greater than 20% savings was demonstrated for building energy consumption by improving facility manager decision support to diagnose energy faults and prioritize alternative, energy efficient operation strategies

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<sup>1</sup> [www.utrc.utc.com](http://www.utrc.utc.com)

- A ROM library for building envelope and HVAC equipment has been developed, validated and tested by using demonstration buildings at Naval Station Great Lakes.
- A prototype toolkit to seamlessly and automatically transfer a Building Information Model (BIM) to a Building Energy Model (BEM) has been developed and tested. This dramatically reduced the time to create a BEM (50% time reduction).
- A tool chain for a scalable probabilistic graphical model based energy diagnostics has been established, tested and demonstrated. Greater than 15% energy savings was achieved by correcting AHU economizer faults. Greater than 95% of faults identified were classified correctly.
- A ROM based HVAC operation sensitivity study has been implemented and greater than 20% energy savings was identified by pre-cooling/preheating the building, resetting chilled water supply temperature setpoints, resetting zone temperature setpoints, and optimizing outside air flow rate in the demonstration buildings.
- A visualization dashboard for building performance energy monitoring, HVAC operation strategies prioritization and energy diagnostics has been developed and deployed in demonstration buildings at Naval Station Great Lakes. This dashboard provides an effective way for building facility managers to perform building performance decision-making.
- Faults and issues identified by the advanced building energy management system were valued by the facility team because the tool provided additional visibility into the building operation that was not provided by the existing traditional building management system. This additional information allowed the facility team to identify previously unknown operational issues and prioritize their maintenance actions.

## **IMPLEMENTATION ISSUES**

The primary concern for the future implementation of the technology is the instrumentation cost. The largest components are the equipment and installation costs related to sub-metering and the on-site weather station. It is possible and reasonable to eliminate the on-site weather station by using weather data from the internet or an existing weather station on the base. There is a need for additional research efforts to establish cost-effective sub-metering.

During the demonstration, the UTC stage-gated technology and product development processes have been applied to begin transitioning the technology into a commercial product. The advanced building energy management system will be a part of a new BMS product or will be applied as an overlay on an existing BMS.

Table 1.1 Performance Objectives Results

Performance Objective	Metric	Data Requirements	Success Criteria <sup>2</sup>	Results
<b>Quantitative Performance Objectives</b>				
Reduce Building Energy Consumption (Energy) & Greenhouse Gas Emissions (CO <sub>2</sub> )	Building total electric consumption (kWh/ft <sup>2</sup> -yr) and peak demand (kW) Building total steam consumption (therm/ft <sup>2</sup> -yr) and peak demand Building total equivalent CO <sub>2</sub> emissions (kg)	Metering data for building electric and steam usage Building simulation data for equivalent CO <sub>2</sub> emissions	>20% reduction in building total energy consumption (over baseline) >15% reduction in building peak demand energy (over baseline) >20% reduction in building total equivalent CO <sub>2</sub> emissions (over baseline)	>20% reduction in building total energy consumption (over baseline) 7~15% reduction in building peak demand energy (over baseline) >20% reduction in building total equivalent CO <sub>2</sub> emissions (over baseline)
Reduce HVAC Equipment Specific Energy Consumption (Energy)	Chiller (kW/ton) Cooling Tower (gpm/ton, kW/ton) AHU (kW/ton) Fan (kW/CFM) Pump (kW/gpm)	Sub-metering data for HVAC equipment	>10% reduction in HVAC equipment energy consumption (over baseline)	5~15% reduction in HVAC equipment energy consumption for AHU, Fan (over baseline)
Reduce Building Loads (Energy)	Lighting loads (kWh) Plug loads (kWh)	Sub-metering data for lighting and plug loads	>10% reduction in lighting or plug loads (over baseline)	>20% reduction in lighting load (Drill Hall) with occupancy control
Building & HVAC System Reduced-order Model (ROM) Validation	Building load (kWh) Building overall energy consumption (kWh/ft <sup>2</sup> -yr) HVAC equipment energy consumption (kWh)	Simulation data from detailed building model (i.e., EnergyPlus) Metering data for building electric and steam usage Sub-metering data for lighting and plugs loads Building measured data	Predicted building loads difference (absolute error) between detailed model and ROM within +/- 10% Overall building energy consumption accuracy within +/- 15% (ROM vs. measurement) HVAC equipment energy consumption accuracy within +/- 10% at the rated conditions (ROM vs. measurement)	Predicted building loads difference (absolute error) between detailed model and ROM within +/- 10% Overall building energy consumption accuracy within +/- 15% (ROM vs. measurement) HVAC equipment energy consumption accuracy within +/- 10% at the rated conditions (ROM vs. measurement)
Advanced Building Energy Management System Robustness	Percentage of faults classified correctly	Building energy fault identified/classified by advanced building energy management system	85% of faults identified are classified correctly (during 3-month demonstration period)	>95% of faults identified are classified correctly

<sup>2</sup> Success criteria related to building and HVAC equipment energy consumption were assessed using both model-based simulations and actual energy measurements.

Advanced Building Energy Management System Payback <sup>3</sup>	Simple payback time SIR (Savings-to-Investment Ratio)	Cost to install and implement advanced building energy management system Savings from using advanced building energy management system	Simple payback time is less than 5 years <sup>4</sup> SIR is greater than 1.25.	Simple payback time is less than 3 years SIR is greater than 2.5.
<b>Qualitative Performance Objectives</b>				
Ease of Use	Ability of an energy manager and/or facility team skilled in the area of building energy modeling and control to use the technology	Feedback from the energy manager and/or facility team on usability of the technology and time required to learn and use	With some training, An energy manager and/or facility team skilled in HVAC able to use the Advanced Building Energy Management System to identify and correct poor HVAC system performance	The user interface was refined based on feedback from facility team. The refined interface was well received.
Interactive and Visual Interface	Ability of an energy manager and/or facility team to effectively make building operation decision by using front-end user interface	Feedback from the energy manager and/or facility team on the interface	An energy manager and/or facility team able to more effectively exploit available building data to improve building operation decision-make	The user interface was refined based on feedback from facility team. The refined interface was well received.
Energy Fault Identification, Classification and Prioritization	Ability to detect, classify and prioritize (based on energy impact) building faults	Building measured data Building simulation data	Energy manager and/or facility team able to detect , classify and prioritize (based on energy impact) building faults by comparing simulated building performance (design intent or optimal) against measured building performance	The system flags faulty behavior via anomaly scores. This information enables facility team to prioritize faults based on energy impacts from simulation models.
Energy Fault Corrective Action Prioritization	Ability to prioritize energy fault corrective actions based on energy impact	Building measured data Building simulation data	Energy manager and/or facility team able to prioritize energy fault corrective actions by comparing the simulated building	By comparing the simulated building energy impact benefits, the system enables facility team to prioritize the fault corrective action.

<sup>3</sup> This payback success criterion is only applied to the case when the only retrofits considered are those that do not involve major equipment retrofits

<sup>4</sup> DoD Energy Managers Handbook <http://www.wbdg.org/ccb/DOD/DOD4/dodemhb.pdf>

			energy impact benefits for each fault corrective action alternative against the simulated or measured baseline building energy performance	
HVAC System Operation Strategies Prioritization	Ability to prioritize the alternative energy efficient HVAC system operation strategies	Building measured data Building simulation data	Energy manager and/or facility team able to prioritize energy efficient HVAC system operating strategies by comparing the simulated building energy impact benefits for each HVAC operation strategy against the simulated or measured baseline building energy performance	Energy manager and/or facility team able to prioritize energy efficient HVAC system operating strategies by comparing the simulated building energy impact benefits for each HVAC operation strategy against the simulated or measured baseline building energy performance
Scalability	Ability of advanced building energy management system to be scaled to different types and sizes of buildings Time to implement the system for a new building	Feedback from the energy manager and/or facility team on scalability; Implementation time for Drill Hall; Implementation time for Building 7113/7114	Type of building: successful demonstrations for office and barracks buildings; Size of building: scale from Drill Hall with smaller floor area to building 7113/7114 with bigger floor area; Implementation time is about 30% less for building 7113/7114 compared with Drill Hall	The aBEMS was successful implemented in Buildings with different type and different size (Building 7230: drill hall and office building with 70,000 sf <sup>2</sup> vs. Building 7113/7114: barracks building with 300,000 sf <sup>2</sup> ).

## 1.0 INTRODUCTION

### 1.1 BACKGROUND

The DoD (Department of Defense) is the largest single user of energy in the United States, representing 0.8% of the total US energy consumed and 78% of the energy consumed by the Federal government [1]. Approximately 25% of the DoD energy use is consumed by its buildings and facilities. The DoD currently has 316,238 buildings across 5429 sites and in 2006 its facility energy bill was over \$3.5B [2]. The Office of the Secretary of Defense (OSD) published an energy policy to ‘ensure that the DoD infrastructure is secure, safe, reliable and efficient’ [3], and subsequent energy policy is being guided by the Energy Policy Act of 2005, Executive Order 13423, and the Energy Independence and Security Act of 2007 to ensure a 30% energy reduction by 2015. Due to the large energy footprint of DoD facilities, increasing building energy efficiency offers the largest opportunity for reducing DoD energy consumption. Building HVAC systems consume greater than 30% of a building’s energy consumption<sup>5</sup> and ensuring sustained, operational efficiencies of building HVAC systems is the focus of this demonstration project.

Studies show that building HVAC systems can consume greater than 20% more electrical energy than the design intent largely because of equipment performance degradation (e.g. filter or heat exchanger fouling), equipment failures, or detrimental interactions among subsystems such as cooling and then reheating of conditioned air [4]. Identifying the root causes of efficiency losses is challenging because gradual erosion of performance can be difficult to detect. Available technologies such as ENFORMA<sup>®</sup> Building Diagnostics<sup>6</sup> exist but focus on detecting equipment level faults and must be programmed using rules. A key barrier is the lack of information at sufficient detail to isolate abnormal changes in load conditions or anomalous equipment operations. While there has been considerable effort to develop and demonstrate advanced methods for building energy diagnostics and HVAC controls [5, 6, 7], the scalable realization of these methods has not been achieved.

To address these challenges in a scalable manner, the United Technologies Research Center (UTRC)<sup>7</sup> performed a demonstration of a building energy management system that employs advanced methods of whole-building performance monitoring combined with statistical methods learning and data analysis to enable identification of both gradual and discrete performance erosion and faults. The system assimilated data collected from multiple sources including blueprints, reduced-order models and measurements, and employed probabilistic graphical models and other advanced statistical learning algorithms to identify patterns of anomalies. The reduced-order model is a simplified model from the simplification of a high-dimensional physical model. The results were presented graphically in a manner understandable to a facilities manager. Importantly, the system incorporated learning algorithms and reduced-order simulation models to circumvent the need to manually construct and maintain a detailed building simulation model. This detailed building model is required for the existing technology (e.g., model-based

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<sup>5</sup>Energy savings are based on 3.8 billion kWh per year of electricity consumed by DOD facilities in 2006 [1].

<sup>6</sup> [www.archenergy.com](http://www.archenergy.com)

<sup>7</sup> [www.utrc.utc.com](http://www.utrc.utc.com)

real-time whole building energy performance monitoring and diagnostics demonstrated in ESTCP project SI-0929) and represents a practical barrier to a broad scalable application.

The demonstration was conducted in three different buildings at the Naval Station Great Lakes. The facility building management systems were extended to incorporate the energy diagnostics and analysis algorithms, producing systematic identification of alternative, energy efficient HVAC operation strategies. More than 20% energy savings for building energy consumption was demonstrated via the implementation of advanced building energy management systems.

Expected Benefits: It is expected that the broad deployment of scalable building energy management systems that apply advanced energy diagnostics and alternative, energy efficient HVAC operation strategies will deliver 20% savings for HVAC energy consumption at DoD facilities. With an annual DoD facility energy spend of \$3.5B, 20% energy savings would offer >\$200M savings potential across all DoD facilities. Achievable annual energy savings amount to 0.8 billion kWh, which offer a reduction of 528,000 metric ton of CO<sub>2</sub> per year<sup>8</sup>. Once the technology is commercialized, it is projected that the \$200M DoD energy savings per year can be applied to the entire US building stock and will result in approximately \$5.3B energy savings per year.

## **1.2 OBJECTIVE OF THE DEMONSTRATION**

The objective of this project is to demonstrate an advanced building energy management system that enables facility managers to visualize building energy performance, diagnose building energy faults, and assess alternative, energy efficient HVAC operation strategies. The demonstration was carried out at Naval Station Great Lakes in Illinois. This project demonstrated the scalability of the advanced building energy management system to different types and sizes of buildings. This project delivered an advanced building energy management system that enables facility managers to visualize building energy performance, diagnose building energy faults, and assess alternative HVAC operation strategies (Figure 1.1). The advanced building energy management system was implemented as a software extension to the current existing Building Energy Management and Control System. For the Naval Station Great Lakes demonstration, this system interfaced directly with the Siemens Building Management System and resided on an independent computer. Prior to the demonstration, there was not any HVAC equipment shakedown/testing.

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<sup>8</sup> CO<sub>2</sub> emission reduction based on US average of 1329 lb of CO<sub>2</sub>/MWh of electricity generated (0.60 metric ton CO<sub>2</sub>/MWh). <http://www.epa.gov/cleanenergy/energy-resources/refs.html>.

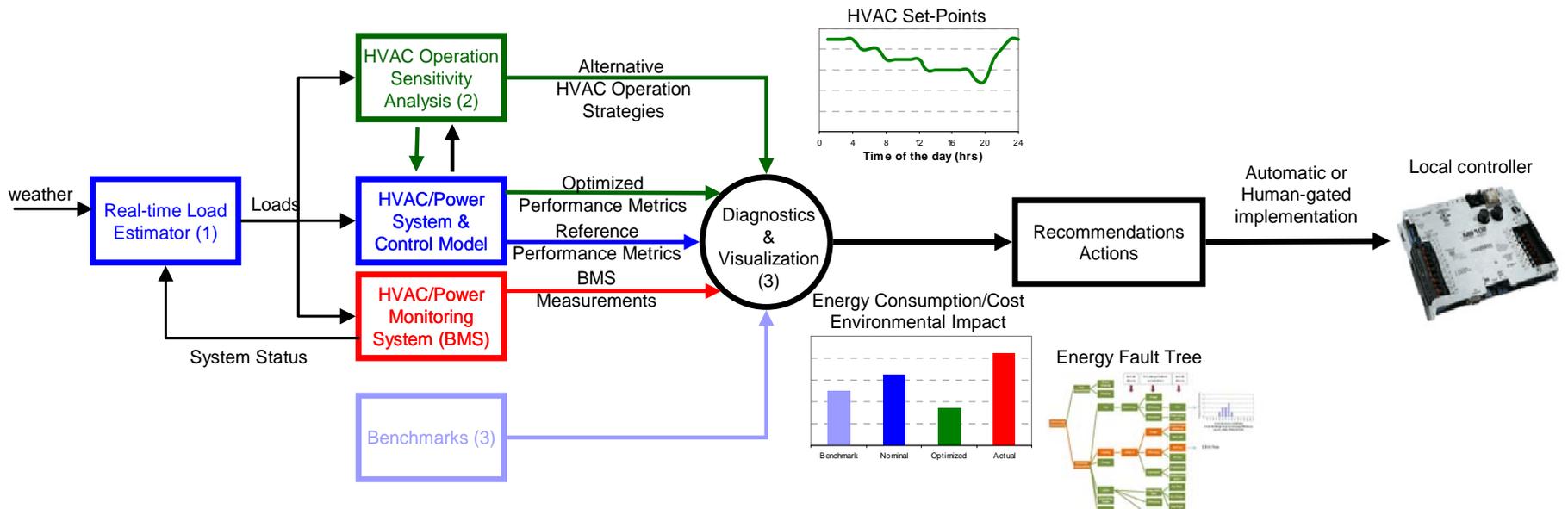


Figure 1.1 Block Diagram of the Advanced Building Energy Management System

This project demonstrated the scalability of the advanced building energy management system to different types and sizes of buildings. Specifically, the scalability of tools and methods for load estimation, reduced-order models for the building and HVAC systems, building and HVAC system energy diagnostics, building and HVAC system energy visualization, and HVAC operation sensitivity analysis was demonstrated.

The demonstrated technology is targeted at commercial buildings that use building energy management systems. The scalability of the solution was also demonstrated by applying 1) load estimation techniques and reduced-order models for the building and HVAC systems, reducing the need for constructing specific, detailed models for each building, and 2) probabilistic graphical models for energy diagnostics, where the graphical structure does not have to be learned for similar equipment and systems every time. The specific technical objectives of the demonstration project were 1) to demonstrate 10% building energy savings by providing the facility engineers with actionable energy fault information to identify and correct poor system performance, and 2) to demonstrate an additional 10% energy savings by identifying alternative energy system operation strategies that improve building energy performance.

### **1.3 REGULATORY DRIVERS**

Executive Order 13423 [8], 13514 [9] and the Energy Independence and Security Act of 2007 (Title IV Subtitle C) require that U.S. federal agencies improve energy efficiency and reduce greenhouse gas emissions by 30% by 2015 relative to a 2003 baseline.

## 2.0 TECHNOLOGY DESCRIPTION

### 2.1 TECHNOLOGY OVERVIEW

The demonstrated technology focused on the scalability of the advanced building energy management system to different types and sizes of buildings. Specifically, the scalability of tools and methods for load estimation, reduced-order models for the building and HVAC systems, building and HVAC system energy diagnostics, building and HVAC system energy visualization, and HVAC operation sensitivity analysis were demonstrated. The project advanced and applied the following key technologies.

- 1) **Load Estimation.** A model-based estimation approach was used to provide information about unmeasured data relative to building energy performance (e.g., internal loads, infiltration, etc.). Estimation was performed using extended Kalman Filters [25], and was based on building reduced-order models. Figure 2.1 shows the schematics of the real time load estimator. Details for the load estimation can be found in Appendix F.

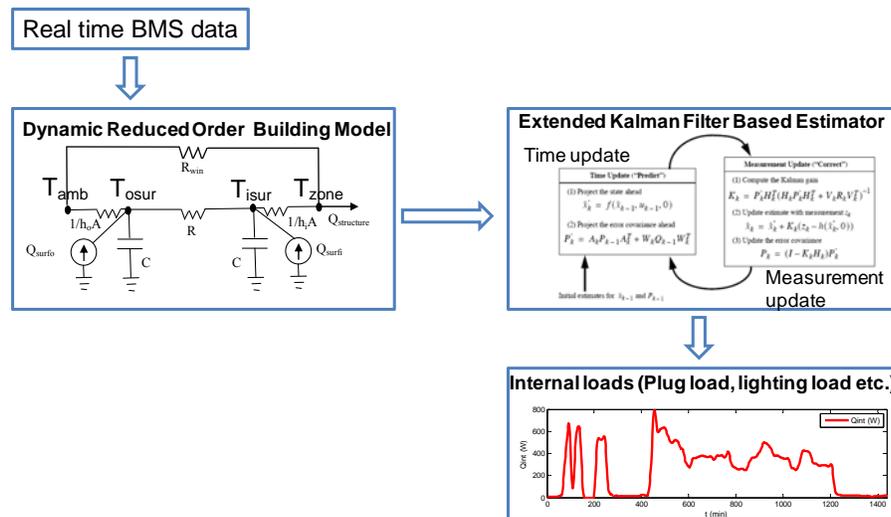


Figure 2.1 Schematics of the Real Time Load Estimator

- 2) **Building Envelope and HVAC System Reduced-Order Models.** Building Envelope and HVAC system reduced-order models were used to predict system energy performance in buildings. Dynamic models are important to explicitly capture the nonlinear and dynamic energy performance in actual buildings (e.g., building envelope thermal mass for the storage). The dynamic coupling that exists between HVAC subsystems also requires models that consider dynamics (e.g., the slow dynamics from the building envelope vs. the fast dynamics from the HVAC equipment; chiller etc.). The building envelope and HVAC system reduced-order models, based on thermodynamics, thermo-fluid laws, and heat transfer analysis, were used for the following: a) as a reference model to represent the ‘as-designed’ building operation; b) to estimate unmeasured variables and energy performance metrics; c) to perform HVAC operation sensitivity analysis to evaluate the impact of various HVAC operation strategies on the building energy performance; and d) to generate the ground truth data (i.e., the baseline) for data driven energy diagnostics.

Table 2.1 shows the developed modules in the building envelope reduced-order model. All modules were validated with measured data from the demonstration site, except for the infiltration model due to lack of data. However, the infiltration module was validated in the literature [24]. The detailed physics of each module are presented in Appendix E. Validation for the building envelope model is included in Appendix A.2.

Table 2.1 Individual Modules in the Building Envelope Reduced-order Model

System	Component	Model	Validation/Verification
Envelope	Solar Radiation	√	√
	Infiltration	√	N/A
	Window Heat Transfer	√	√
	Wall Heat Transfer	√	√
	Air Heat Balance	√	√
	Internal Load Generator	√	√
	Automatically generated ODE	√	√
	BIM generated model	√	√

N/A: No data available for validation/verification

Models have been created for the HVAC equipment in the demonstration buildings as listed in Tables 2.2 and 2.3. Models created in Building 7230 were reused in Building 7112/7114 for similar equipment. These models are lumped steady-state reduced-order models (ROM's). The models can be used for energy monitoring and trend analysis. They are not intended for distributed thermo-fluid or detailed control study. Models have been calibrated and validated when appropriate measured data was available. For equipment without measured data or with low-quality data, models have been examined with trends and ranges based on fundamental physics. Details for the model validation procedure and methodology are included in Appendix A.1.

Table 2.2 List of HVAC System Reduced-Order Models for Building 7230

System	Equipment	Quantity	Model	Validation/Verification
Primary	Chiller	2	√	√
Secondary (AHU)	Cooling coil	4	√	√
	Heating coil	4	√	N/A
	Fan	8	√	√
	Economizer	4	√	*
	Pump	2	√	√
Terminal	VAV with reheat	7	√	*
	Duct Free Split System (DFSS)	2	√	N/A
	Unit heater	10	√	N/A
Utility	Psychrometrics	13	√	√
	Iteration solver	1	√	√

Table 2.3 List of HVAC System Reduced-Order Models for Building 7113/7114

System	Equipment	Quantity	Model	Validation/Verification
Primary	Absorption chiller	2	√	**
	Cooling tower	1	√	Verification
	Condenser pump	3	√	√
Secondary (AHU)	Cooling coil	10	√	N/A
	Heating coil	8	√	N/A
	Heat recovery coil	4	√	N/A
	Supply fan	10	√	√
	Return fan	10	√	√
	CHW pump	3	√	√
	HW pump	4	√	√
	Heat recovery pump	4	√	N/A
	Economizer	10	√	*
	Terminal	VAV	238	√
Other	Unit heater (water)	5	√	N/A
	Unit heater (electric)	6	√	N/A
	Exhaust fans	39	√	VFD fans
Utility	Psychrometrics	15	√	√
	Iteration solver	1	√	√

\* Inconsistent controls for some units. (e.g., minimal damper positions specified by the control design document were not in the actual operation)

\*\* Measured data of the condensate flow rate for heat inputs need to be improved

N/A: No data available for the validation/verification

The reduced-order models do not require detailed descriptions of the equipment such as geometry and structure; therefore they can be readily reused or scaled for reuse. The HVAC system reduced-order models have been used for various model based studies including performance monitoring, controls and diagnostics. Although model formats can be kept the same, model parameters should be calibrated with the test data for a given system. Detailed descriptions of HVAC equipment models are included in Appendix G. Validation results of HVAC equipment models can be found in Appendix A.1.

The integrated building system model was developed based on previous implemented building envelope and HVAC system reduced-order models. The integrated model has four parts: 1) model initialization; 2) HVAC control logic; 3) coupling of the building envelope model with HVAC system models; and 4) interface with the building database and BMS. The overall schema of the integrated system model is illustrated in Figure 2.2. The integrated system model runs in the MATLAB [10] simulation environment. The coupling between the building envelope and the HVAC system models uses a “ping-pong” approach. At each time-step, the building envelope model passes the loads of all zones into the HVAC system model. The HVAC system model then calculates the required airflow and supply air temperature for each zone, which become inputs for the

next time step. The Extended Kalman Filter [25] has been implemented to estimate the uncertain parameters and/or inputs in the integrated model such as thermal capacitances and resistances of walls, internal mass of zones, and internal loads. The estimation module is scheduled to run every two weeks or can be invoked on demand.

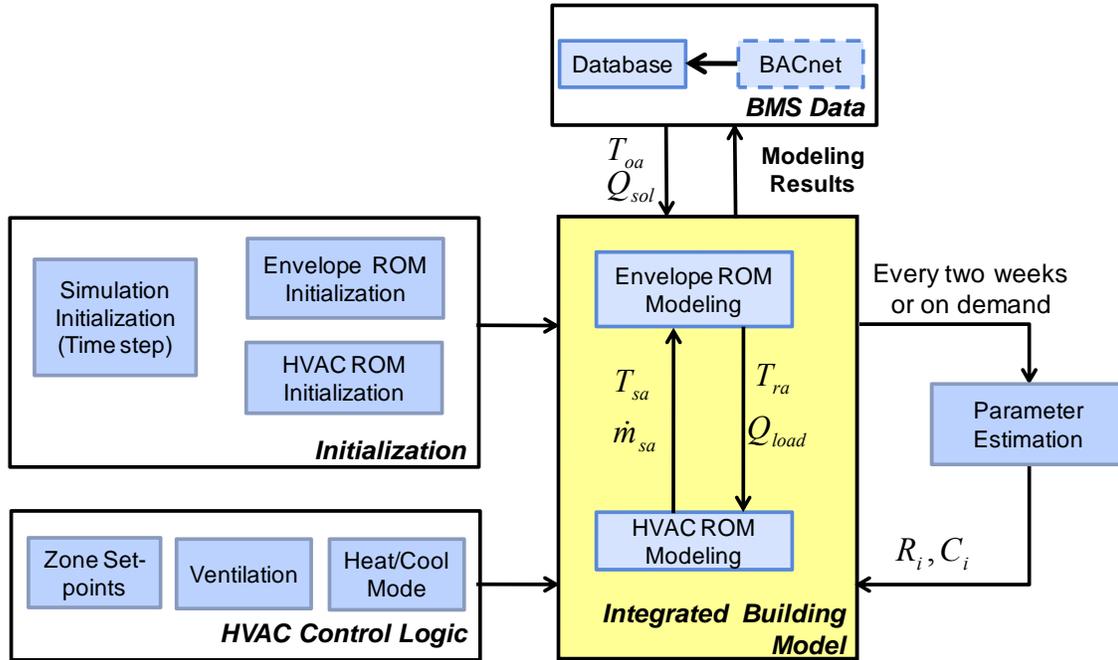
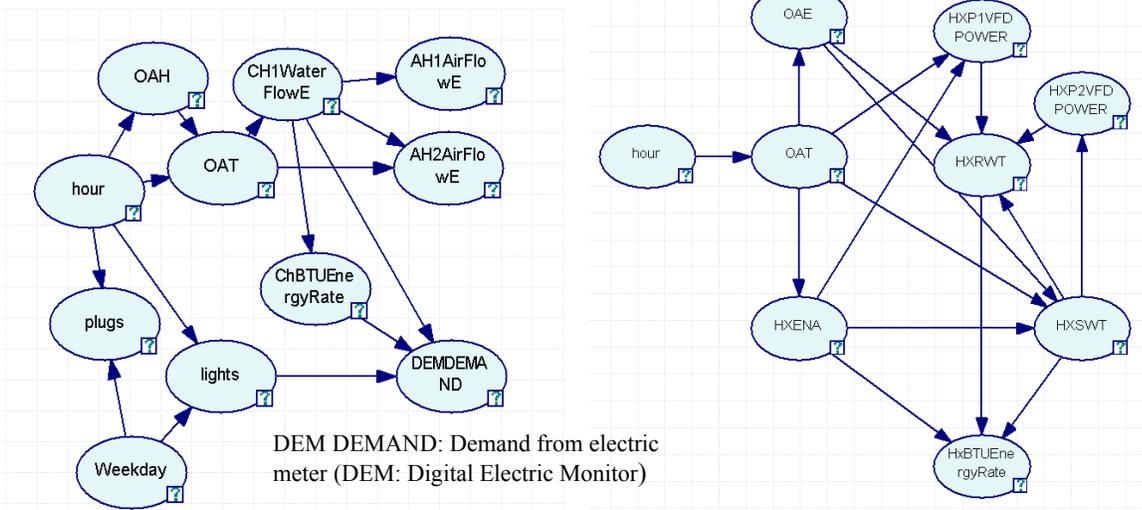


Figure 2.2 Overall Schema of Integrated System Model

- 3) **Building and HVAC System Energy Diagnostics.** Building and HVAC system data represents a hierarchical structure of power usage and the delivered heating/cooling throughout the building. Identifying at which level in this hierarchy a fault-cause occurs is crucial to effectively provide facility management decision support. Building and HVAC system energy anomalies were detected and decision support methods were used to direct the facility manager to the likely root causes that were prioritized by the magnitude of the energy impact. To perform energy diagnostics, data mining and model-based estimation approaches were used to provide energy anomaly detection. A number of complementary modeling methods were used to implement energy diagnostic decision support. These include probabilistic graphical models [11, 12] and expert rule-based threshold methods [26]. For example, the system level diagnostic model and one of its component diagnostic models for Building 7230 are shown in Figure 2.3.



*System level graphical network*

*Component level heat exchanger graphical network*

Figure 2.3 Diagnostic Models for Building 7230

The graphical structure is learned from operational data by discovering the relationships between measured variables. The goal of this step is to learn the nominal behavior of the system. After this step the learned graphical structure is validated against domain knowledge and physics based understanding of the system. At this point the graphical network model for Fault Detection and Diagnostics (FDD) is used to analyze new data to generate an anomaly score quantifying the difference between a variable's predicted state and its measured value. Based on the anomaly scores and a suitably chosen threshold, faults are detected & diagnosed by identifying anomalous variables. Details about the probabilistic graphical model based FDD can be found in Appendix H.

- 4) **Energy Performance Visualization Tool.** The current state-of-the-art building management systems (BMS) provide facility managers with a rich set of building data. This building data includes system and equipment performance (temperature, pressure, energy consumption of building systems, etc.), controller status, and equipment fault status. However, the interconnected complexity and large volume of this building data often complicate facility manager decision-making. Today, facility managers rely on their personal intuition and experience to perform building operation decision-making. This project developed an interactive, visual interface for facility managers to more effectively exploit available building data to improve building operation decision-making. The energy performance visualization tool enables: a) visualization of energy-related metrics at different building and HVAC systems levels; b) decision support to enable the identification and prioritization of alternative, energy efficient HVAC system operating strategies for facilities engineers; c) energy fault diagnostics and root cause analysis; and d) identifying persistent trends in energy usage. The energy performance visualization tool provided an interactive user interface for facility manager to access building energy operational data.

The Integrated Buildings Energy and Diagnostics Visualization (iBED Viz) tool, developed in this project, provides an intuitive interface to view energy utilization at the building level and for major components, i.e., lighting, plug loads, heating, cooling, fans and pumps.

Advanced visualization features for easy navigation and drill-down analysis have also been implemented. The diagnostics interface takes a top-down approach which allows the operator to see building level health performance as well as component level health performance using a hierarchical building interface that lists key system components such as the chiller, heat exchanger and air handling units (AHU). Key features of the iBED Viz visualization system (highlighted in Figures 2.4, 2.5 and 2.6) are discussed in Appendix H.

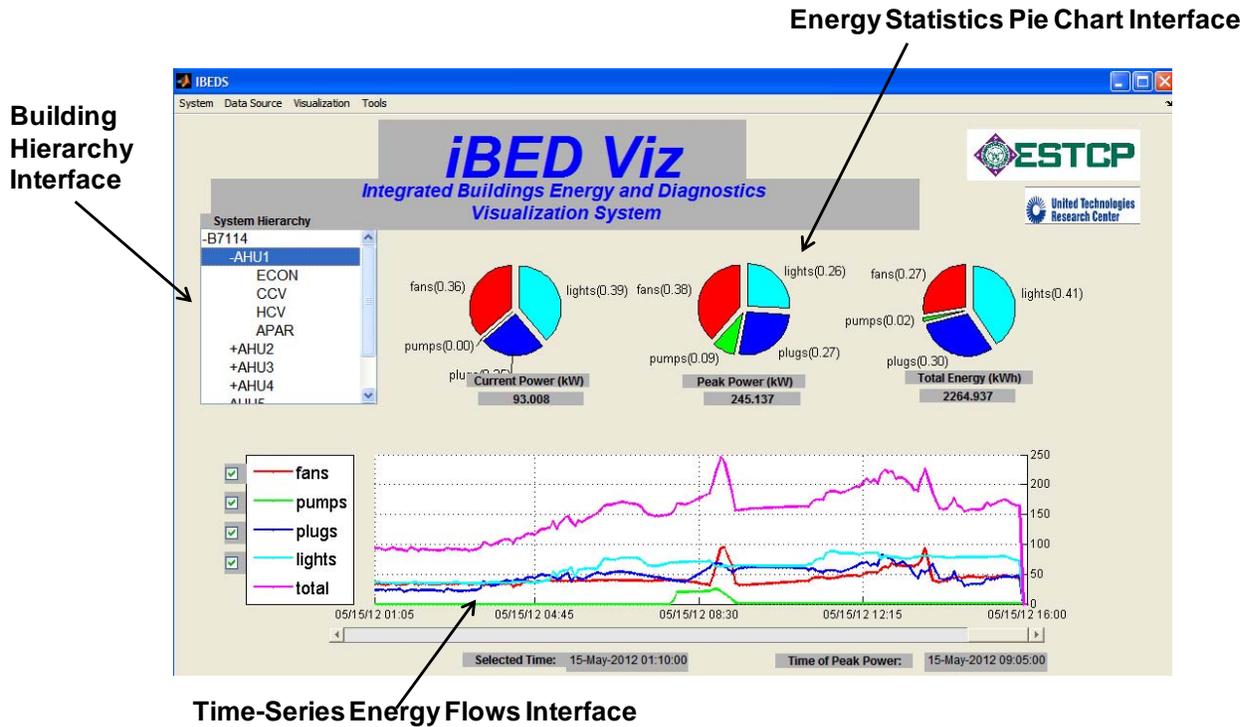


Figure 2.4 Overview of the Energy Visualization Interface

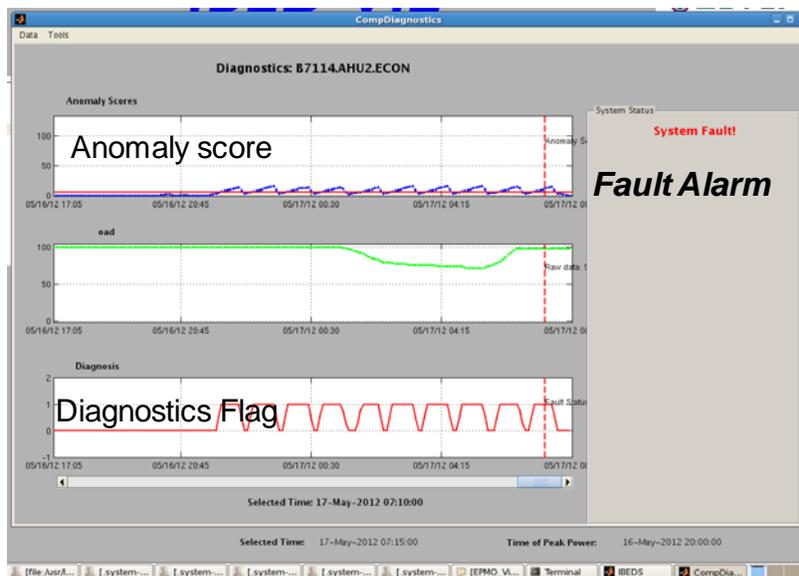


Figure 2.5 A Screenshot of FDD Interface

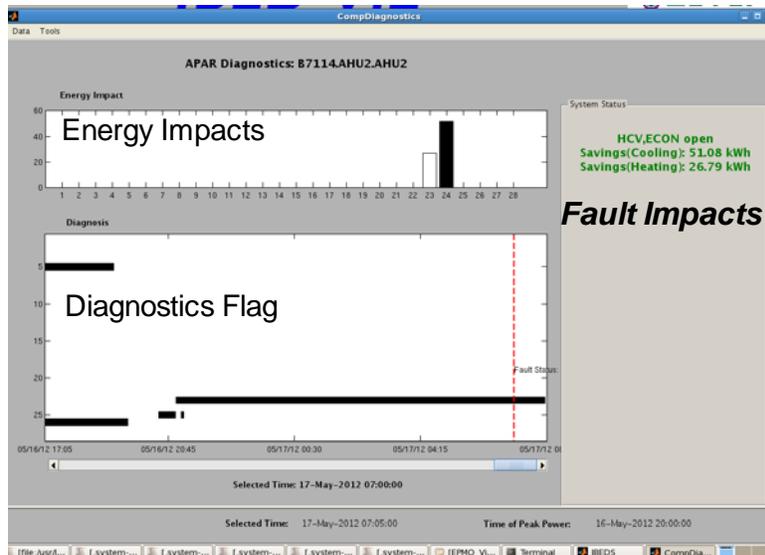


Figure 2.6 A Screenshot of Fault Energy Impacts Interface

- 5) **HVAC Operation Sensitivity Analysis.** The current state-of-the-art building management systems do not readily provide facility managers with the capability to identify or prioritize alternative HVAC operation strategies that could deliver energy savings. Often, HVAC system energy improvement measures are down-selected for implementation without a rigorous assessment of the impact on the target building or HVAC system operation. The integration of the ROM for the building and HVAC systems with energy performance visualization offer an opportunity to rigorously assess energy impact of alternative HVAC operation strategies before and after implementation. HVAC operation sensitivity analysis methods were implemented within the energy performance visualization framework to allow the facility manager to identify and prioritize energy efficient HVAC operation alternatives for implementation. Both single and simultaneous multivariable sensitivity analysis methods were implemented. As an example, single variable sensitivity analysis will allow the facility manager to assess if an increase or decrease in chiller supply water temperature setpoints will cause higher or lower system level energy consumption. A multivariable sensitivity analysis will allow the facility manager to identify more complex operation strategies that will lead to overall lower energy consumption. For example, what direction and by how much should the chiller water supply temperature set-point and fan speeds be modified when load conditions vary.

An HVAC operation sensitivity study based on the integrated ROM offers a great opportunity to rigorously assess energy impact of alternative HVAC operation strategies before and after implementation. Both single and simultaneous multivariable sensitivity analysis methods were implemented for Building 7230 and Building 7113/7114 based on the integrated building system model. Details about the operation sensitivity study can be found in Appendix A.3. The unique feature of the HVAC operation sensitivity study within the advanced building energy management system is that it compares the energy savings from different operation scenarios and provides actionable recommendations to the facility team. (Please refer to Figures H.15 and H.16 in Appendix H for examples).

- 6) **Building Data Acquisition System.** A Building Data Acquisition System (BDAS) was developed to acquire data from the BMS. The current version is able to acquire data from any BACnet protocol compatible system. In the future this software may be expanded to cover other protocols. The current version is based on the Building Control Virtual Test Bed (BCVTB) environment [13]. The following functions are supported by the BDAS system:
- Get data from systems that support BACnet protocol
  - Store data in a database

Details about the BDAS can be found in Appendix I.

- 7) **Building Information Model (BIM) to Building Energy Model (BEM) Tool Kit.** A desirable building life cycle delivery process should include design, construction, commissioning and post-occupancy evaluation. It involves tremendous information storage and exchange. Although there are BIM based design tools such as Revit to represent building data for design and there are currently no tools available to systematically translate building design data into building operational BEM. This results in a time consuming and error prone building energy modeling, and also impacts the results of model-based FDD. To address this issue, a BIM to BEM toolkit was developed. This toolkit includes a BIM-based database and automatically simulation code generation. Details for this toolkit can be found in Appendix J.

## 2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The broad, scalable application of building energy management systems that apply advanced methods for HVAC operational controls and energy diagnostics to DoD's facilities is a key for achieving the DoD's energy reduction targets. Ensuring that the energy management decisions made by DoD facility managers is based on a building monitoring system that raises the visibility of energy performance is key for delivering building energy savings.

The tangible DoD energy benefits are 20% savings for building energy consumption at DoD facilities where 10% is achieved through improved visibility of building energy diagnostics that provide facility engineers actionable data to identify and correct poor system performance and an additional 10% reduction achievable by providing HVAC set-points that would optimize system performance. With an annual DoD facility energy spend of \$3.5B and a 20% building energy reduction achieved through the application, the aBEMS would offer >\$200M savings potential across all DoD facilities. Achievable annual energy savings amount to 0.8 billion kWh<sup>9</sup>, which offers a reduction of 528,000 metric ton of CO<sub>2</sub> per year<sup>10</sup>.

The intangible DoD benefits are to provide consistent energy management practices utilized by its facility managers through increased visibility into equipment performance, better informed decisions on maintenance and operational issues, improved forecasting of equipment life and equipment replacement and upgrade programs, and a reduction in emergency equipment failures. Ultimately energy benchmarking and best-practice sharing across DoD facilities can also be achieved.

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<sup>9</sup> Energy savings are based on 3.8 billion kWh per year of electricity consumed by DOD facilities in 2006 [1].

<sup>10</sup> CO<sub>2</sub> emission reduction based on US average of 1329 lb of CO<sub>2</sub>/MWh of electricity generated (0.60 metric ton CO<sub>2</sub>/MWh). <http://www.epa.gov/cleanenergy/energy-resources/refs.html>.

The advanced building energy management system differs from existing Energy Information Systems (EIS) in the following ways:

- This system augments an existing BMS with additional sensors/meters and uses a reduced-order model and diagnostic software to make performance deviations visible.
- Existing systems neither provide a viable means to quantify the value of a proposed HVAC operation strategy, nor a methodology to quantify the value of different strategies. This system employs a physics-based ROM sensitivity study that is useful to estimate the economic value of different HVAC operation strategies. This actionable information will facilitate the facility manager's decision-making process.
- Compared to purely rule-based technologies such as PACRAT [14], this system uses a scalable physics-based ROM together with data mining techniques such as probabilistic graphical network models for rigorous energy diagnosis.
- Existing systems do not provide a means to calculate and visualize the energy impact due to faults.

The technical risks and the corresponding mitigations are summarized as follows:

- 1) The model accuracy is crucial for model based HVAC operation sensitivity studies. A load estimator was used to provide more realistic internal load input profiles to the model. Model calibration is very important and can be handled well by using auto-tuning tools [15].
- 2) The effectiveness and reliability of the data mining methods are directly related to the quality of the data collected (data gaps, inconsistent sensors, lack of full system information). Risk mitigation includes 1) supplementing the data with inputs derived by physics-based models, statistics and domain knowledge, and 2) sensor diagnostics.
- 3) The corrective actions to correct faulty operation or other deficiencies identified by the tool may require modifications to building systems that are outside the scope of this contract or substantial capital expenditures that are beyond the means of this contract. Mitigation efforts were focusing on modifications to the control system that are realizable with minimal effort, and also on relatively simple fixes to the HVAC or lighting systems that fall within the expertise of the team and local facility staff.
- 4) The relatively high implementation cost is a major limitation. The largest components are the equipment and installation costs related to sub-metering and the on-site weather station. It is possible and reasonable to eliminate the on-site weather station by using weather data from the internet or an existing weather station on the base. A detailed cost analysis is provided in Section 6. To address this challenge, a low cost and scalable building energy monitoring system should be the focus of one of the future research efforts (see Appendix K for the details). This system should include:
  - A comprehensive design guideline to determine the minimum set of sensors for deploying energy monitoring systems in DoD buildings;
  - Virtual sensors derived from physical based models;
  - Low cost, scalable building electrical and thermal energy sub-metering;

- Middleware that provides seamless data acquisition and automated point mapping into the advanced building energy management systems;
  - Automated sensor health monitoring that combines heuristic rules, physics based models and data mining algorithms.
- 5) A deployment concern for this technology is the skill level required to install and maintain the system. A user manual and training for end users such as facility managers and building operators is necessary.

### 3.0 SITE/ FACILITY DESCRIPTION

#### 3.1 SITE/FACILITY LOCATION AND OPERATIONS, AND CONDITIONS

The first demonstration site was Building 7230, the Naval Atlantic Drill Hall, at Naval Training Center, Great Lakes, IL. Building 7230 is a two-story facility with a drill deck, office, and administrative rooms. The gross area of this building is approximately 69,218 ft<sup>2</sup>.

The second demonstration sites were Buildings 7113 and 7114 at Naval Training Center, Great lakes, IL. Building 7113 is a 149,875 ft<sup>2</sup> recruit barracks and is a long rectangular building, consisting of a large block of berthing compartments, heads (bathrooms), laundry rooms, classrooms, a quarterdeck with a two-story atrium and office spaces, and a large cafeteria/galley. Buildings 7113 and 7114 are functionally similar (i.e., include barracks, classroom, and cafeteria etc.) and share a common central chilled water plant.

Figure 3.1 shows the location of Building 7230 (Drill Hall), Building 7113 and 7114

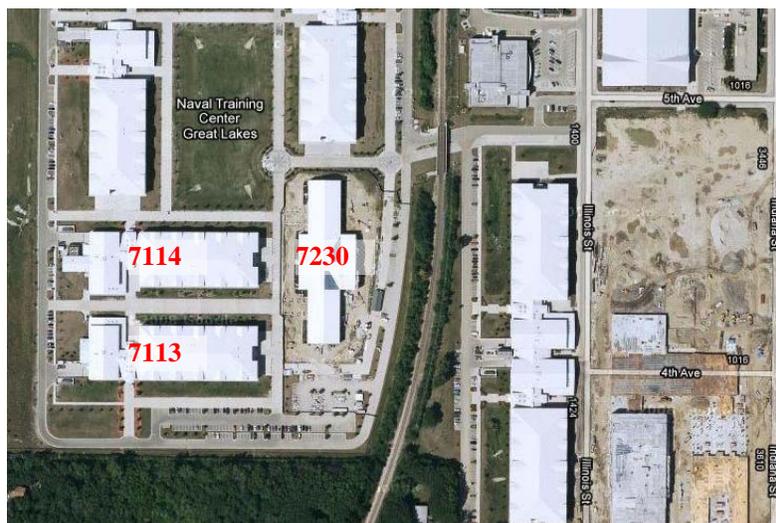


Figure 3.1 Location of Buildings 7230, 7113 and 7114

#### **Building 7230**

The Drill Hall (Building 7230) HVAC system consists of four airside systems and two separate waterside systems. The drill deck is supplied by two variable-air volume (VAV) air handling units with heating and cooling capability. Operation of these units depends on the occupancy of the drill deck space. Double-walled sheet metal ductwork with a perforated liner and drum louvers distribute the air throughout the space. The office and administrative area is served by one VAV air handling unit with VAV terminal units (with hot water reheat). The classroom is served by one VAV air handling unit. The chilled water system consists of two 100-ton air-cooled rotary-screw type chillers with fixed-speed primary pumping and variable-speed secondary pumping. Heating is supplied from the existing base-wide steam system through a steam-to-water heat exchanger. The hot water serves unit heaters, VAV box reheating coils, and air handling unit heating coils. There is an instantaneous steam-to-domestic hot water generator

for domestic hot water service. The server room and communication service room are served by dedicated split systems. Table 3.1 lists major HVAC equipment used in building 7230.

Table 3.1 Major Equipment Used in Building 7230

Equipment	Number	Manufacturer
Duct free split system	2	Carrier
Air cooled screw chiller	2	Carrier
Variable volume AHU	4	Carrier
Suspended unit heater	7	Vulcan
Cabinet unit heater	3	Vulcan
VAV box with hot water reheat coil	8	TITUS
Pumps	7	Bell & Gossett

### Building 7113/7114

When Building 7113/7114 was occupied by recruits, the building was occupied 24 hours a day for seven days a week. Recruits spent about 85% of their time in the barracks. Recruits left the barracks for drills and marches and during personal time on Sunday and holidays. The HVAC equipment in Building 7113 is located in five (5) mechanical rooms and an attic space. Building 7114 shares the absorption chillers, cooling tower, heating hot water heat exchangers, chilled water pumping system, heating hot water pumping system, and the condenser water pumping system with building 7113. The following equipment is used in Building 7113.

Table 3.2 Major Equipment Used in Building 7113

Equipment	Number	Manufacturer
Air Cooled Condensing Unit	1	--
Variable volume AHU	5	Trane
Exhaust fan (in mechanical room)	12	--
Roof Exhaust Fans For Dining/Galley	7	--
Hot water unit heater	3	Vulcan
Electric unit heater	3	Vulcan
Drying Room Cabinet Unit Heaters	18	Vulcan
VAV box with hot water reheat coil	81	TITUS
VAV box without hot water reheat coil	48	TITUS
Pumps	1	Bell & Gossett
Coil run around heat recovery systems	2	--

The HVAC equipment in Building 7114 is located in six (6) mechanical rooms and attic space. The following equipment is used in Building 7114.

Table 3.3 Major Equipment Used in Building 7114

Equipment	Number	Manufacturer
Air Cooled Condensing Unit	1	--
Steam to hot water heat exchanger	2	--
Absorption chiller	2	Trane
Variable volume AHU	5	Trane
Exhaust fan(in mechanical room)	12	--
Roof Exhaust Fans For Dining/Galley	7	--
Hot water unit heater	3	Vulcan
Electric unit heater	3	Vulcan
Drying Room Cabinet Unit Heaters	18	Vulcan
VAV box with hot water reheat coil	162	TITUS
VAV box with hot water reheat coil	81	TITUS
VAV box without hot water reheat coil	48	TITUS
Pumps	12	Bell & Gossett
Coil run around heat recovery systems	2	--
Cooling Tower	1	BAC

A distributed Direct Digital Control (DDC) system, APOGEE™ Insight by Siemens Building Technologies is installed in Buildings 7230, 7113 and 7114. This system monitors all major lighting and environmental systems. Building electric meters are also read by the DDC system. Operator workstations provide graphics with real-time status for all DDC input and output connections.

The energy manager and facility team at Naval Station Great Lakes were willing to endorse and support the demonstration from the beginning of the demonstration. The demonstrated advanced building energy management system was implemented as an overlay on the existing BMS and had no directly interfaces with the HVAC equipment and system operation in the demonstration buildings. The advanced building energy management system provided actionable information about building operation such as HVAC system/equipment health status and fault priority list based on energy impacts etc. Currently, the communication between the existing BMS and the advanced building energy management system is one-way, and building operators have the authority to take final actions based on the information provided by advanced building energy management system.

### 3.2 SITE/FACILITY IMPLEMENTATION CRITERIA

The implementation of the aBEMS depends on the existing building control system communication capability. In general, the aBEMS can be applied to any commercial buildings with a BMS. It is desirable that the existing BMS in the building supports an open communication protocol such as BACnet, LonWorks, or Modbus. For the buildings that are not compatible with these open communication protocols, the BMS vendor can provide data drivers to make the building operational data available.

Another criterion for site selection is whether the building is undergoing a major renovation or has the renovation plan in the near future. The aBEMS is intended to apply to buildings that are operating in a relatively stable state.

Based on building stock information extracted from the DoD's real property asset database (RPAD<sup>11</sup>) and from CBECS<sup>12</sup> database, there are 31,461 buildings across the DoD with an area greater than 10,000 ft<sup>2</sup>. It is likely that a BMS exists in these buildings and the demonstrated advanced building energy management system will be applicable.

To reduce the initial cost associated with the advanced building energy management system, DoD should begin to mandate that DoD facilities to install energy meters at the intermediate level recommended by the ASHRAE performance measurement protocols<sup>13</sup>. This will support an enhanced level of understanding of building performance and to identify possible areas of performance improvement through the use of the advanced building energy management system.

Energy meters include:

- HVAC total electric
- HVAC fan electric
- Chiller plant electric
- Nonelectric heating (other fuel)
- Electric heating, when significant electrical that is present
- Indoor lighting total electric
- Miscellaneous electric (Plug loads)
- Thermal BTU meters for chilled water loop and hot water loop
- Thermal BTU meters for hot water loop

### **3.3 SITE-RELATED PERMITS AND REGULATIONS**

- Regulation: None
- Environmental Permit: None
- Agreements: None

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<sup>11</sup> The RPAD database contains a total of 216985 buildings.

<sup>12</sup> Commercial Building Energy Consumption Survey (CBECS) <http://www.eia.gov/consumption/commercial/>

<sup>13</sup> ASHRAE. 2010. Performance Measurement Protocols for Commercial Buildings

## **4.0 TEST DESIGN AND ISSUE RESOLUTION**

### **4.1 CONCEPTUAL TEST DESIGN**

The technology was demonstrated in two phases at Naval Station Great Lakes.

Phase 1 targeted a single building (Great Lakes Building 7230). Building 7230 is a Navy drill hall and represents buildings with large interior spaces. Integrated reduced-order models (building envelope and HVAC systems) were constructed and calibrated based on as-built drawings and other reference material. Building instrumentation was deployed and data was collected. Tasks included energy diagnostics and decision support methods, energy visualization tool, and HVAC operation sensitivity analysis methods. They were implemented to improve building performance at Great Lakes.

Phase 2 demonstrated the scalability of the proposed approach, and expanded the capabilities developed for a single building to a building campus at Naval Station Great Lakes (Buildings 7113, 7114, 7230). The scalability issues addressed in Phase 2 considered demonstration across buildings of different and similar types. Building 7113 represents a multi-function building that includes barracks, classroom, and cafeteria that is functionally different from Building 7230. Buildings 7113 and 7114 are functionally similar (i.e., include barracks, classroom, and cafeteria) and share common central chilled water plant and were also used to demonstrate the scalability to buildings of different size. The objective for Phase 2 was to demonstrate the scalability of the advanced energy management systems to a campus level at Naval Station Great Lakes. Scalability addressed how reduced-order models and estimation methods for building and HVAC systems, and the energy diagnostics, visualization, and HVAC operation sensitivity analysis can be reused.

Additional metering is required to calibrate models and accurately measure energy consumption to validate results. For Building 7230, the existing instrumentation system from ESTCP project SI-0929 [16] was utilized with additional measurements (i.e., chilled water BTU meters at the AHU local level). For Buildings 7113 and 7114, sub-meters (DEM) were installed to measure lighting and plug loads at building level. BTU meters were installed for both hot water and chiller water loops. The steam consumption for absorption chillers was monitored through condensate meters. Details about the additional instrumentation for Building 7113/7114 can be found in Section 4.3. These sensors/meters were integrated into the existing Siemens BMS, and a prototype middleware interface was installed to enable information flow to a Personal Computer (PC) located within the building. This PC also hosted the aBEMS.

### **4.2 BASELINE CHARACTERIZATION**

An existing operation baseline model was used in this project. The existing operation baseline model is a reduced-order model (both building envelope and HVAC systems) that represents the current building operational practice. The model inputs include a description of the building (e.g., location, orientation, geometry, shading, envelope material and construction), weather, lighting and plug load profiles, occupancy and the HVAC system sequence of operation. The model computes the building energy consumption for the HVAC system, lighting and plug loads at a 5-minute interval.

The building description was obtained from the design documentation and as-built drawings. In the case where some of the information was not available, either an on-site investigation or an empirical estimate was used to determine these parameters. The HVAC system sequence of operation was obtained by combining the information from the control design documents, the existing BMS programs, and interviews with the building operators. The weather data was collected from the augmented instrumentation (i.e., on site weather station). The lighting and plug load profiles were estimated from the additional building level sub metering. The real occupancy profiles for classrooms and compartment areas were derived from the motion sensor data. If the motion count exceeded 5 within 5 minutes, the space was considered to be occupied. Load profiles were also assessed using a load estimator. A model-based estimation approach was used to provide estimates of internal loads within the building. The estimation is built using a building reduced-order model from the building thermal network and measured data (e.g., temperatures, airflow rates) from the BMS, with considerations for sensor noise and model uncertainties. Appendix F provides the details for the load estimator. After the initial model is built, a calibration process was applied to match the simulation results with the measured data by tuning the model input data. An uncertainty analysis was also performed to quantify model accuracy.

The building envelope and HVAC system reduced-order models are based on thermodynamics, thermo-fluid laws, and heat transfer analysis. These models were used in the following ways: a) as a reference model to represent the ‘as-operated’ building operation; b) to estimate unmeasured variables and energy performance metrics; c) to perform HVAC operation sensitivity analysis to evaluate the impact of various HVAC operation strategies on the building energy performance; and d) to generate the ground truth data for probabilistic graphical model based energy diagnostics.

### **4.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS**

#### **Instrumentation and Monitoring**

The required measurement points and measurement accuracy have been taken from the *Specifications Guide for Performance Monitoring Systems* (<http://cbs.lbl.gov/performance-monitoring/specifications/>).

##### **1) Building 7230**

The existing instrumentation system from ESTCP project SI-0929 [16] was used. This includes an on-site weather station, electric sub-meters for chillers, lighting and plug loads, and thermal BTU meters for hot water loop and chilled water loop. Additional BTU meters (including a matched pair of supply and return chilled water temperature sensors and water flow measurements) at the AHU level were installed as shown in Figures 4.1 and 4.2.

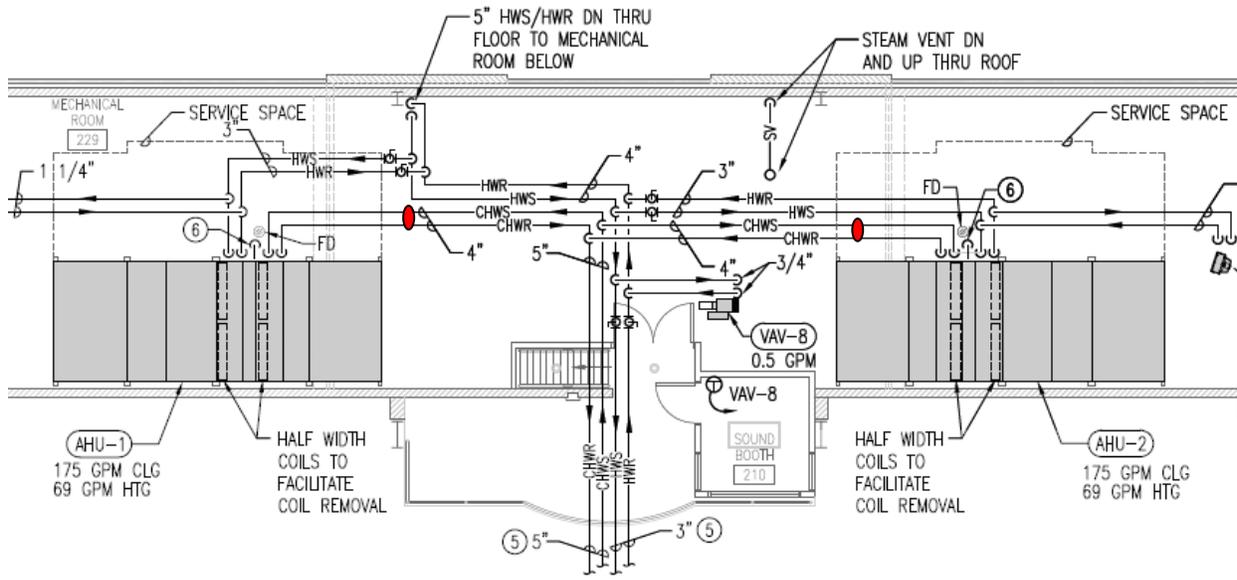


Figure 4.1 Approximated Locations for BTU Meters at AHU1 and AHU2 in Building 7230

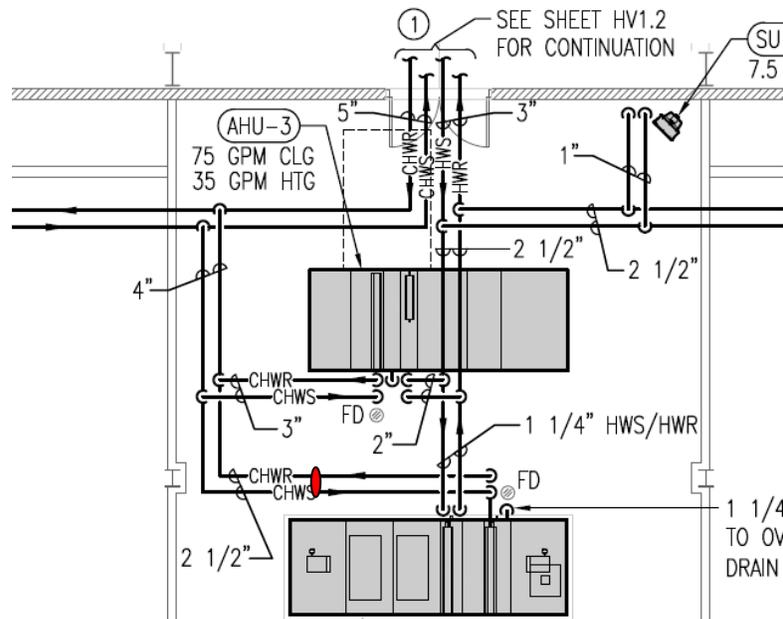


Figure 4.2 Approximated locations for BTU meters at AHU4 in Building 7230

## 2) Building 7113/7114

The additional hardware and software necessary to implement the advanced building energy management system in Building 7113/7114 are listed in Table 4.1. All of the building performance monitoring points that were required for the demonstrated system are listed in Table 4.2. Approximately 2773 points were mapped from Siemens BMS system to the demonstrated system. The cost estimates for these monitoring points are provided in Section 6. The installation details and exact locations were determined on site with the subcontractor that installed and

calibrated the equipment. Approximated locations for the additional instrumentation are shown in Figure 4.3 to 4.7.

Table 4.1 Additional System Tool Components for Building 7113/7114

Component	Quantity	Note
PC	1	Window XP, 2.5GHz processor speed, 1 GB memory, 250 GB hard drive, UPS is recommended.
Siemens BACnet Server	1	Establish the communication capability between the Siemens APOGEE™ system and the demonstrated system (data acquisition).

Table 4.2 Performance Monitoring Points List for Building 7113/7114

Point needed	Status		Note
	New	Existing	
Outside air temp	X		Aspirated weather station is required.
Outside air wet bulb	X		
Pyranometer	X		
Wind speed/direction	X		
Building pressure		X	
Main power meter		X	
Lighting load power	X		The approximated locations are shown in Figure 4.3. (the actual location may be slightly different due to differences between as-built drawing and actual layouts)
Plug load power	X		The approximated locations are shown in Figure 4.4.
Absorption chiller steam condensate meter	X		The approximated locations are shown in Figure 4.7.
CHW secondary pump power		X	Utilize the VFD power measurement.
CHW supply temp	X		Matched pair sensors are recommended and the approximated locations are shown in Figure 4.5.
CHW return temp	X		Matched pair sensors are recommended and the approximated locations are shown in Figure 4.5.
CHW flow meter	X		The approximated locations are shown in Figure 4.5.
HW pump power			Utilize the VFD power measurement.
HW supply temp	X		Matched pair sensors are recommended and the approximated locations are shown in Figure 4.6.
HW return temp	X		Matched pair sensors are recommended and the approximated locations are shown in Figure 4.6.

HW flow meter		X	The approximated locations are shown in Figure 4.6.
Condenser fan power			Utilize the VFD power measurement.
AHU supply fan power		X	Utilize the VFD power measurement.
AHU return fan power		X	Utilize the VFD power measurement
Zone temperatures		X	
Zone relative humidity (RH)		X	
VAV box damper position		X	
VAV box flow		X	
VAV box reheat coil valve		X	
AHU supply air Temperature		X	
AHU mixed air temperature		X	Average sensors are recommended.
AHU return air temperature		X	
AHU static pressure		X	
AHU air flow		X	
AHU heating coil		X	
AHU cooling coil		X	
AHU economizer damper position		X	

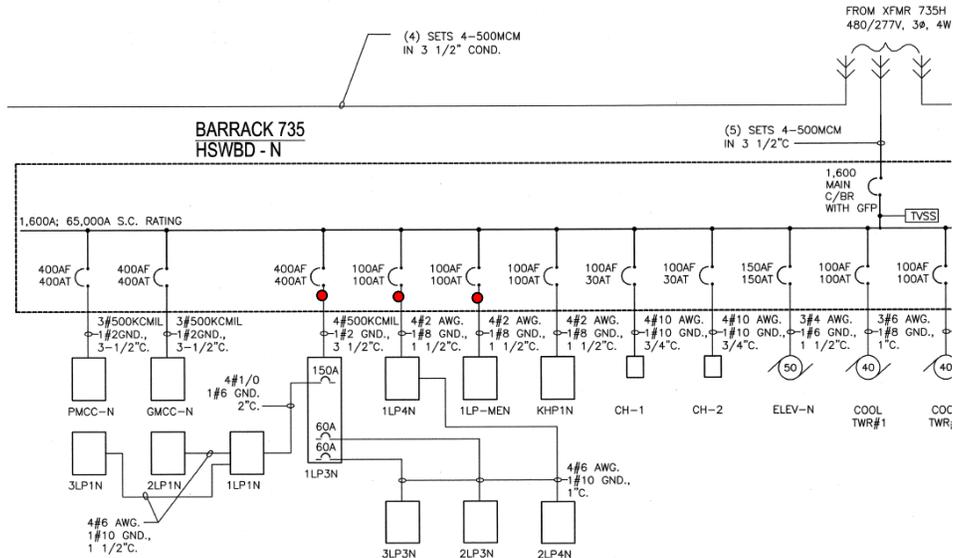


Figure 4.3 a) Approximated Locations of Additional Power Meters/CTs (Lighting Loads):  
Sub-meters for Lighting Loads in (Building 7114)

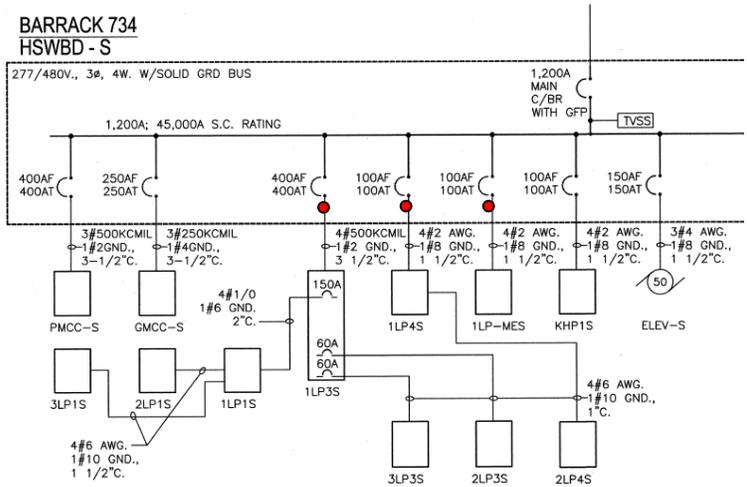


Figure 4.3 b) Approximated Locations of Additional Power Meters/CTs (Lighting Loads):  
Sub-meters for Lighting Loads (Building 7113)

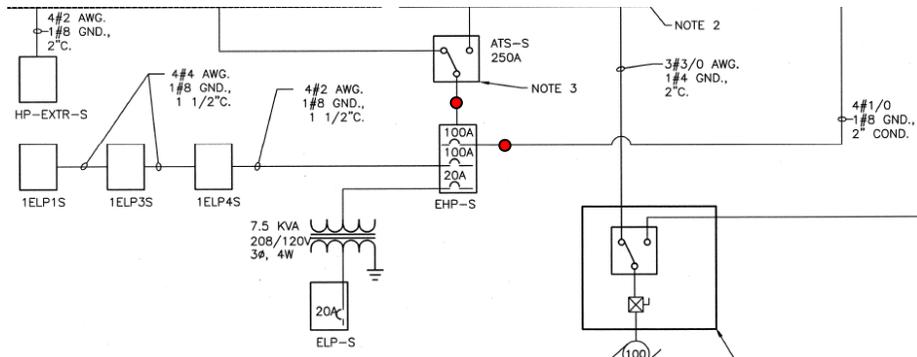


Figure 4.3 c) Approximated Locations of Additional Power Meters/CTs (Lighting Loads):  
Sub-meters for Emergency Lighting Loads (Building 7113/7114)

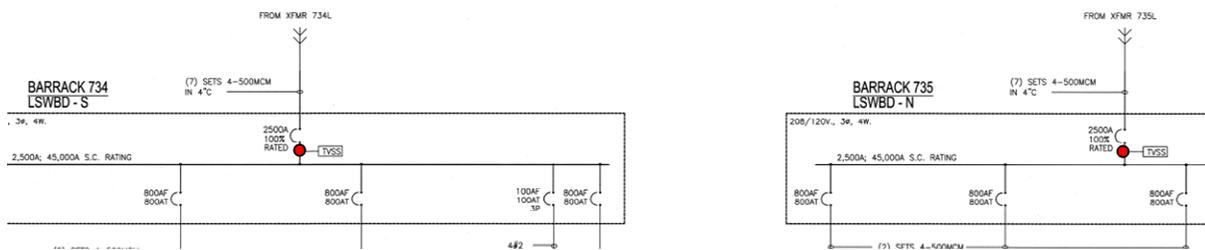


Figure 4.4 Approximated Locations of Additional Power Meters/CTs (Plug Loads):

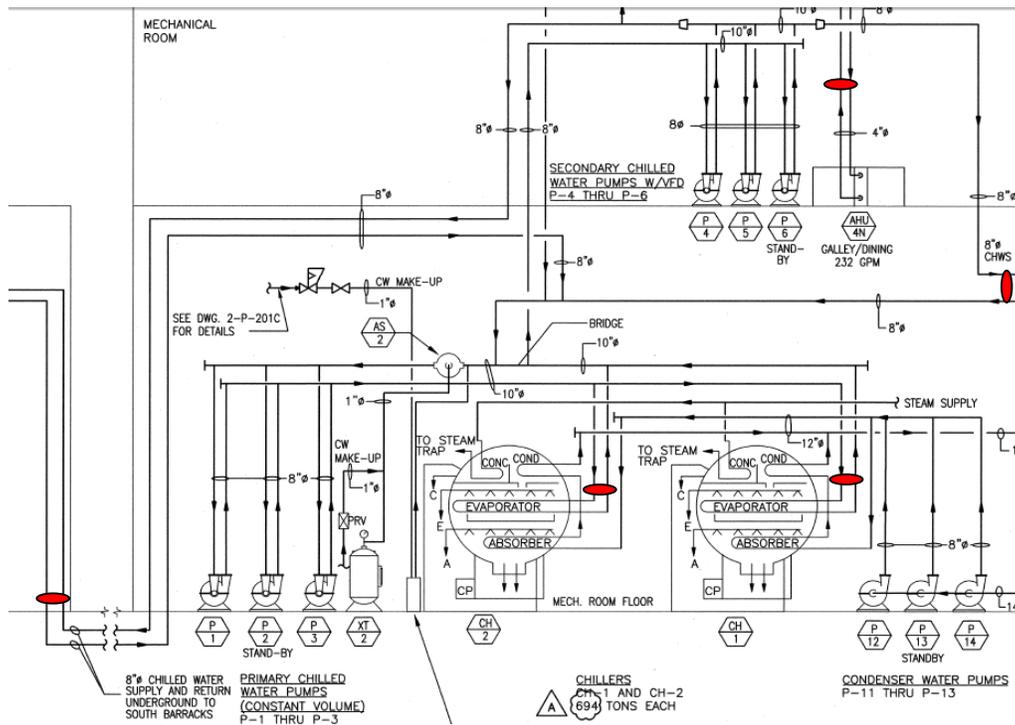


Figure 4.5 Approximated Locations for Chilled Water BTU meters

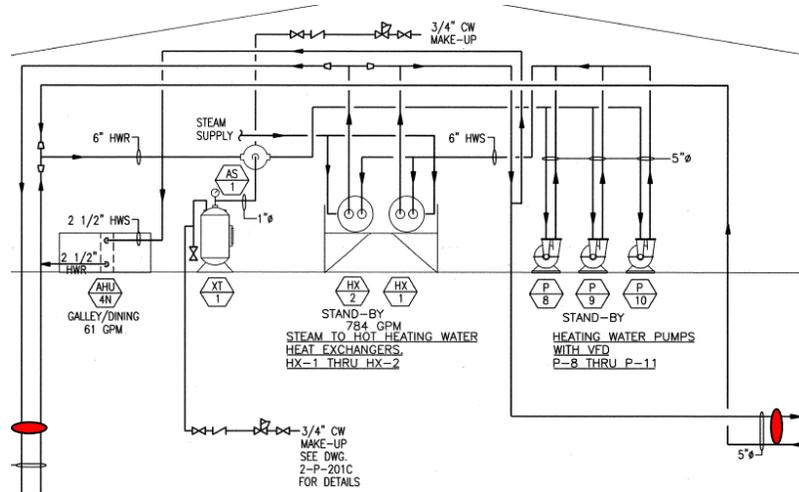


Figure 4.6 Approximated Locations for Hot Water BTU Meters

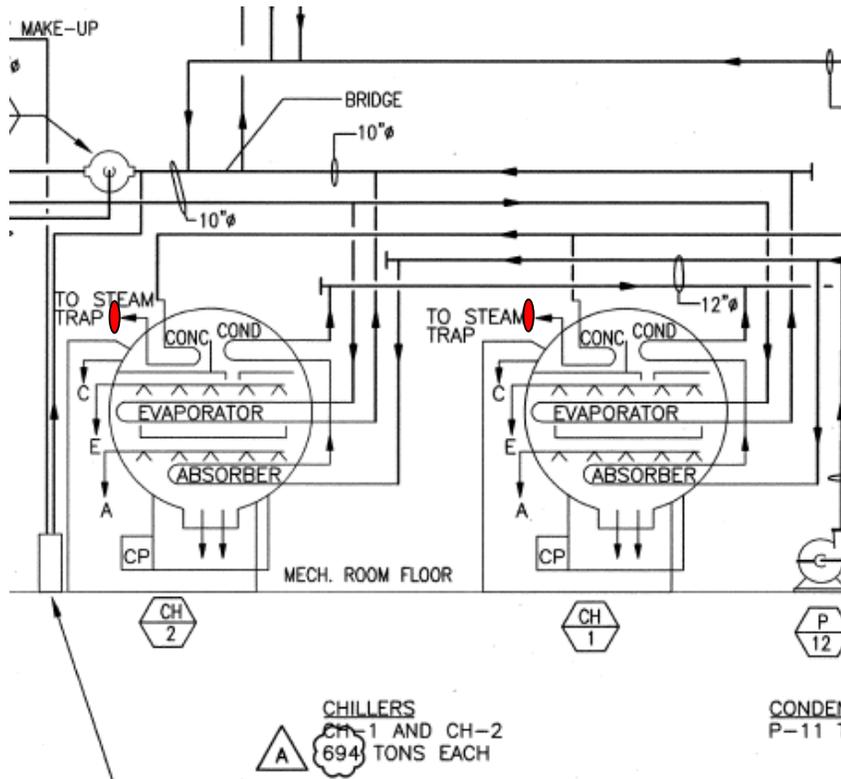


Figure 4.7 Approximated Locations for Absorption Chiller Steam Condensate Meters

#### 4.4 OPERATIONAL TESTING

There were two demonstration phases. Phase 1 targeted a single building (Great Lakes Building 7230). Phase 2 demonstrated the scalability of the proposed approach, and expanded the capabilities developed for a single building to a building campus at Naval Station Great Lakes (Buildings 7113/7114).

### Phase 1: Building 7230 Off-Line Demonstration

The off-line demonstration for Building 7230 was conducted from 07/01/2010 to 03/31/2011. This phase began right after the additional building instrumentation had been installed and calibrated. There were four activities in this phase:

- The building ROM was assessed through a direct comparison between the ROM building modeling approach and the detailed building model approach (i.e., the EnergyPlus model used in ESTCP project SI-0929). The building ROM model was also tested against the ASHRAE 140 standard - Method of Test for The Evaluation of Building Energy Analysis Computer Programs [17]. The test results are included in Appendix E. The outcome from this assessment was a “Go” decision for the ROM building modeling method to be applied in phase 2.
- The project team calibrated the ROM using the building measurement data. During this phase, the required data was acquired from the existing Siemens BMS and stored in a database to make it available for the off-line demonstration. Data was used to: 1) calibrate the reference ROM and 2) identify potential system energy faults and to identify opportunities for corrective actions.
- A manual process was used to analyze the building performance by comparing the measured data and the reference ROM outputs. This analysis quantified the performance deviation in terms of energy impact and identified root causes for potential faults. The ROM was also used to conduct the preliminary HVAC operation sensitivity study for different HVAC operation strategies in Building 7230 (See Table A.4 in Appendix A).
- The offline demonstration of the advanced building energy management system for Building 7230 was setup on a PC at the UTRC’s Integrated Building Energy and Control Laboratory. There were four main components: integrated building model module, database module, FDD module and visualization module. The measured data from Building 7230 was stored in the database for the period of May 2010 to December, 2010. A building information model (BIM) data base was designed to have a relational database schema to facilitate the storage of building operational data and FDD analysis data. The integrated model reads data from the database every five-minute, runs the simulation and stores the results back into the database. The FDD model runs every one hour. Visualization was triggered when requested by the user. Figure 4.8 shows the overview of offline demo integration structure.

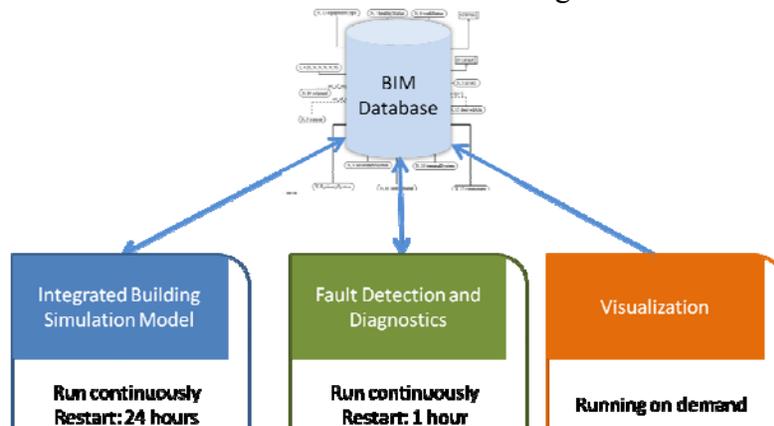


Figure 4.8 Overview of Offline Demonstration Integration Structure

## Phase 2: Building 7113/7114 On-Site Demonstration

This onsite demonstration in Building 7113/7114 was conducted from 04/01/2011 to 04/30/2012. This phase began right after the off-line demonstration in phase one. The schematic diagram for an online implementation of the advanced building energy management system is shown in Figure 4.9. The computer server running the aBEMS is located in the same building location as the PC running the Siemens BMS. The required building performance data was collected through the existing BMS and made accessible to the advanced building energy management system through a data acquisition module.

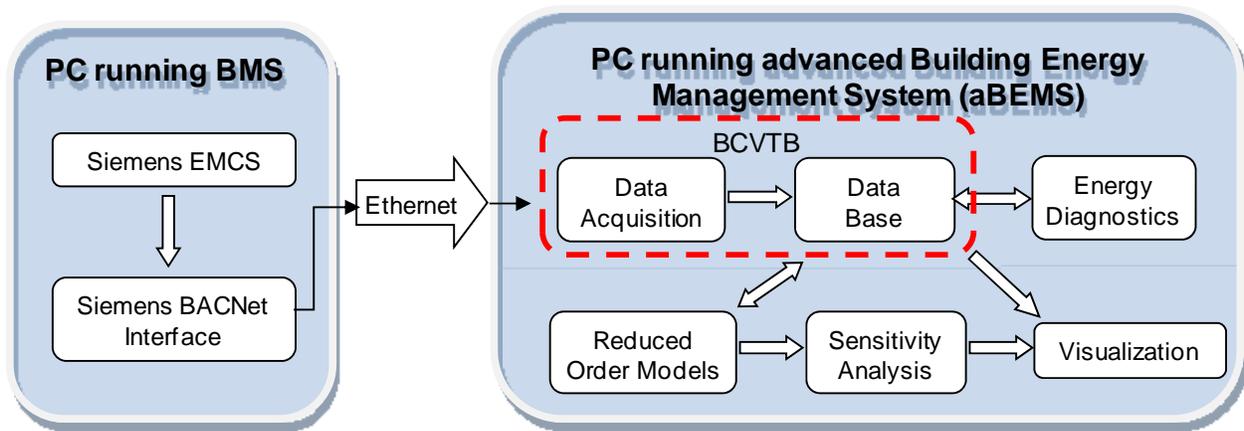


Figure 4.9 Advanced Building Energy Management System (aBEMS) Schematic Diagram

Within the advanced building management system there are several modules necessary to achieve the system functional requirements for an on-site demonstration. The Data Acquisition module, developed from the open source Building Control Virtual Testbed (BCVTB), is used to acquire the relevant measured building performance data from the Siemens BACnet interface through an Ethernet connection. The Data Acquisition module also transfers the data to the Data Base module which is storing data into the database. The sampling interval for this demonstration is 5 minutes. The calibrated ROM module that represents the design/optimal building performance is receiving data (e.g., weather data, estimated loads) used by the simulation and executing the reference ROM at each 5 minute interval. The ROM simulated results then are passed back to the Database module where the results are stored in the database. The Sensitivity Analysis Module uses the ROM to prioritize different HVAC operation strategies and results are stored in the database.

The Energy Diagnostic module is used to execute the diagnostic tool at every four hours. The Energy Diagnostic tool communicates directly with the Database to retrieve historical data (building measurements and building reference model predictions). The Energy Diagnostic tool applies data mining and anomaly detection methods to identify building faults. The database stores all the relevant building performance data and ROM simulation results every 5 minutes and stores the Energy Diagnostic tool results (faults and recommendations) every four hours. The database used in this demonstration is PostgreSQL. Any Structured Query Language (SQL) database (e.g., MySQL) can be integrated to the aBEMS. The visualization is the user front-end interface to demonstrate the results as well as to display the measured building performance data. Visualization is triggered whenever requested by the user.

The aBEMS was running as an application on a computer at Building 7113/7114 to automatically and/or semi-automatically invoke the different functional modules (Data Acquisition, Database, ROM, Energy Diagnostics, and Sensitivity Analysis). A visual user interface application was available on the PC desktop. This user interface application allowed the facility team to plot a comparison of building energy consumption data, the ROM output and sensitivity analysis results. The user interface application also allowed the facility team to automatically identify what building performance metrics are anomalous and where corrective actions should be prioritized. Figure 4.10 shows the demonstration system in Building 7113/7114, which is located in the Building 7114 penthouse.

At the end of the demonstration, the advanced building energy management system was left in place and turned over to the site facility management team.



Figure 4.10 Demonstration System in Building 7113/7114

#### 4.5 SAMPLING PROTOCOL

The existing Siemens APOGEE™ BMS collects all the building performance data, including the additional measurement data proposed by this project. The data communication within APOGEE™ is done with a Siemens proprietary protocol. In order to acquire the relevant data for this demonstration project, an APOGEE™ BACnet interface was installed. This BACnet interface allows the existing Siemens BMS to exchange data with an external data acquisition system through the BACnet protocol. A sampling frequency of 5 minutes was selected to ensure the collection of sufficient data to represent the real-world building operating conditions.

BACnet is a communications protocol for building automation and control networks. It is an ASHRAE, ANSI, and ISO standard protocol. BACnet was designed to allow communication of building automation and control systems for applications such as heating, ventilating, and air-conditioning control, lighting control, access control, and fire detection systems and their associated equipment. The BACnet protocol provides mechanisms for computerized building automation devices to exchange information, regardless of the particular building service they perform.

The data acquisition module in the demonstrated system acquires building performance data from the Siemens BACnet interface. The communication was established through an Ethernet

connection. Data quality control information is provided in Section 4.6 and relevant building performance sampling points are presented in Tables 4.1 and 4.2 in Section 4.3.

## **4.6 EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES**

### **Calibration of Equipment**

All the equipment specified in Section 4.3 was calibrated when installation was complete. The calibration procedures strictly followed manufacturer guidelines<sup>14</sup>.

During the building performance monitoring period, the team assessed sensor drift for the data points collected from the BMS. The team applied a data statistical analysis protocol that computes various statistics to ensure computed values are within acceptable ranges. Specifically, data for each measured point was used to compute the minimum value, maximum value, mean (average) and standard deviation. If the computed values were outside of the reference range, the data was flagged and further analyzed to identify the root cause. The majority of measurement points were directly from the existing BMS, where the controller vendor (e.g., Siemens at Great Lakes) closely monitored these points based on control industry standards and protocols to make sure that all the measurements were within the acceptable accuracy band.

### **Quality Assurance Sampling**

Data quality is very important for the performance of the aBEMS. The sampling frequency has an effect on the type of faults that the system can detect. In general, a faster sampling frequency is better. Since the goal was to detect the energy related faults, a five-minute sample frequency was used. Scripts were used to automatically remove the duplicated data and spiked samples from raw data, synchronize data, and output clean, conditioned data for an analysis within the system.

Missing data is possible even though the instrumentation and monitor systems are designed and commissioned to be reliable. Statistical methods such as extrapolation, interpolation and trend analysis, augmented by domain expertise, were applied to fill in the missing data.

For quality assurance sampling, the team took the following approaches:

- Duplicates – Two measurements for some important points were deployed in the building system. For example, there were duplicated temperature measurements for both hot water and chilled water. The current BMS already has water temperature sensors. Additional paired water temperature sensors (supply and return) were installed at the appropriate location. This improved reliability and quality of the data collected.
- Spiked samples – Spiked samples are defined as measurements that are taken for certain points and then compared against expected values obtained in “laboratory setting”. Spiked samples are used to measure accuracy. For the sensors used in building systems such as temperature sensors and flow sensors, it is difficult to have spiked sample testing after these sensors are in

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<sup>14</sup> BTU meters; <http://www.onicon.com/System10.shtml>

Outside air temperature <http://www.vaisala.com/en/products/humidity/Pages/HMT330.aspx>

Electric meter (DEM):

[http://cn.siemens.com/cms/cn/English/SBT/downloading/Building\\_Automation\\_Product\\_Home/Direct\\_Digital\\_Controller/Documents/DEM/DEMElectricalSeries10002000Datasheet\\_EN\\_1173020.pdf](http://cn.siemens.com/cms/cn/English/SBT/downloading/Building_Automation_Product_Home/Direct_Digital_Controller/Documents/DEM/DEMElectricalSeries10002000Datasheet_EN_1173020.pdf)

place. However, these sensors have been tested and calibrated before the installation. For example, temperatures sensors are usually calibrated in the lab for certain points such as 0°C (ice-water mixture) and 100°C (water boiling point).

- Blanks samples - Blank samples are clean samples, produced in the field, used to detect analytical problems during the whole measurement process. In the automated continuous commissioning system, blanks samples were created when the building was in normal operation in order to establish and calibrate a baseline model.

### Data Analysis

Quality of the data acquired from the BMS is crucial for the success of this project and a data quality review is an integral aspect of the implemented approach. Robust data quality evaluation includes testing for precision, accuracy, representativeness (including sampling rate and latency issues) and completeness of the data.

Data precision [18] is how close agreement exists between sensor values obtained by replicating measurements on the same or similar objects under specified conditions. Precision is used to define measurement repeatability and measurement reproducibility. Repeatability is the variability of a measurement when keeping all controllable and uncontrollable factors constant. It is typically measured by taking data very close together in time, under similar conditions in a laboratory setting. Reproducibility is the variability due to specific controllable or uncontrollable factors by observing measurements at various system configurations. Typical statistical techniques used to accomplish this are analysis of variance and analysis of covariance methods. The team used the specification sheets provided by sensor manufacturers as a guideline but in cases where sensors didn't perform as expected; further analysis and in-house testing were performed.

In addition to the above steps, the data collected from the BMS is subjected to a protocol that computes various statistics on the data to ensure computed values are within acceptable ranges. These values were computed periodically for various lengths of time and the values were compared with reference values obtained from the accuracy analysis (using spiked values or duplicates when appropriate). If the computed values were outside of the reference range, then the data was flagged and further analyzed to identify and (and possibly discard) any spurious data points. This process served as a final sanity-check before the data was used for diagnostics.

## 4.7 SAMPLING RESULTS

Table 4.3 lists summary information regarding the data collected in this project. All the data is stored in the PostgreSQL database residing on the host PC in Great Lakes.

Table 4.3 Building Data Facts

Building	Data points	Sampling frequency	Duration	Measurement variables
BLDG7230	688	5 minutes	04/12/2010 to present	Temperatures, water flow rates, air flow rates, damper/valve positions, duct pressure, setpoints, control outputs (command)
BLDG7113/7114	2733	5 minutes	03/03/2011 to present	

Figures 4.11 to 4.15 show example data plots for data taken from Building 7114 from August 5<sup>th</sup>, 2011 to August 25<sup>th</sup>, 2011.

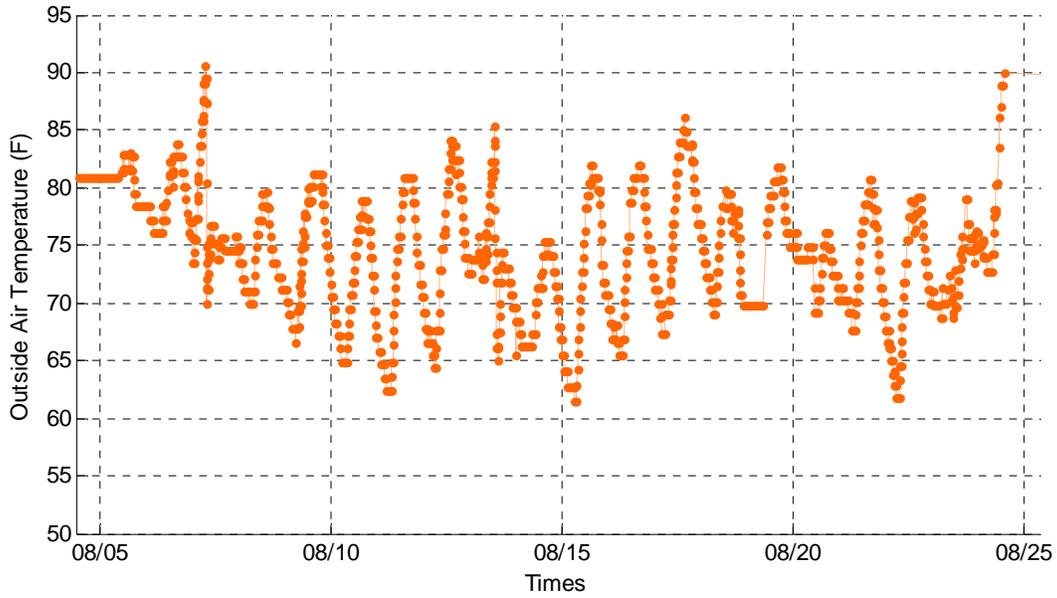


Figure 4.11 Building 7113/7114 Outside Air Temperature

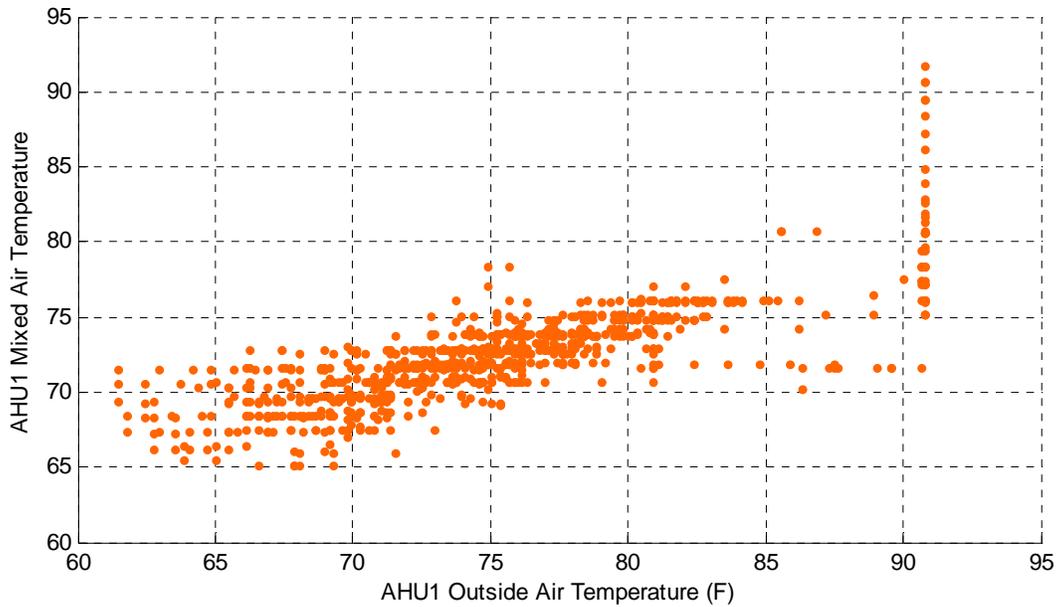


Figure 4.12 Building 7114 AHU1 Mixed Air Temperature vs. Outside Air Temperature

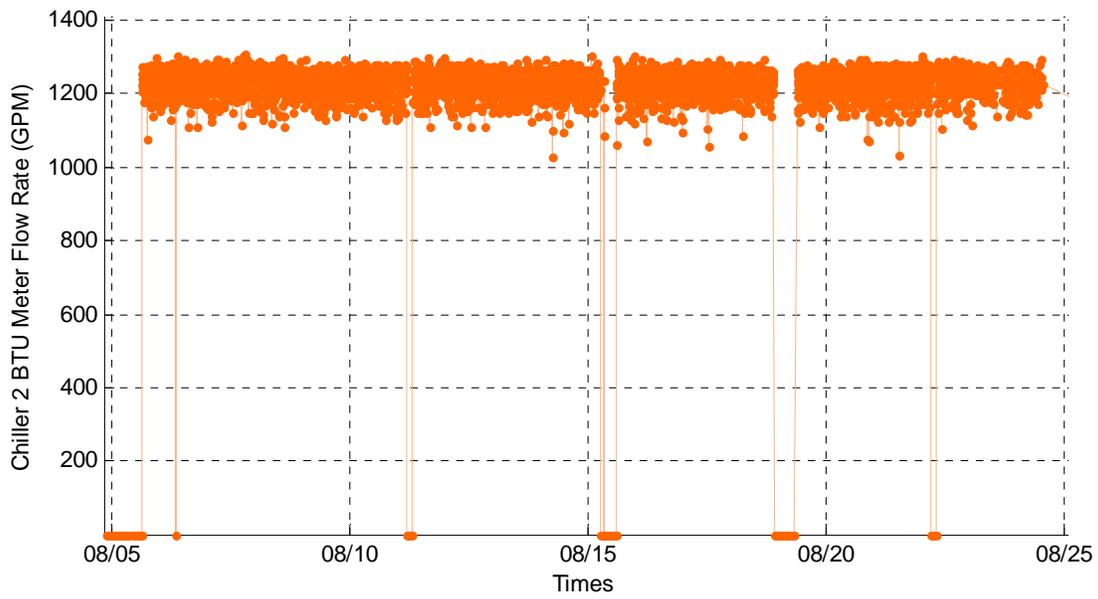


Figure 4.13 Building 7114 Chiller 2 Chilled Water Flow Rate

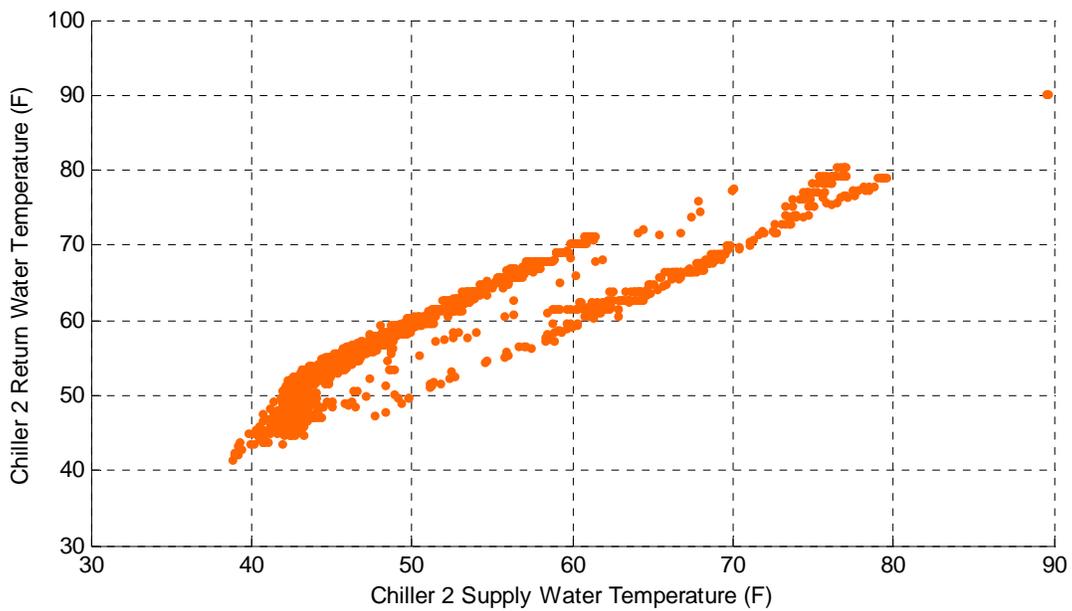


Figure 4.14 Building 7114 Chiller 2 Supply Water Temperature vs. Return Water Temperature

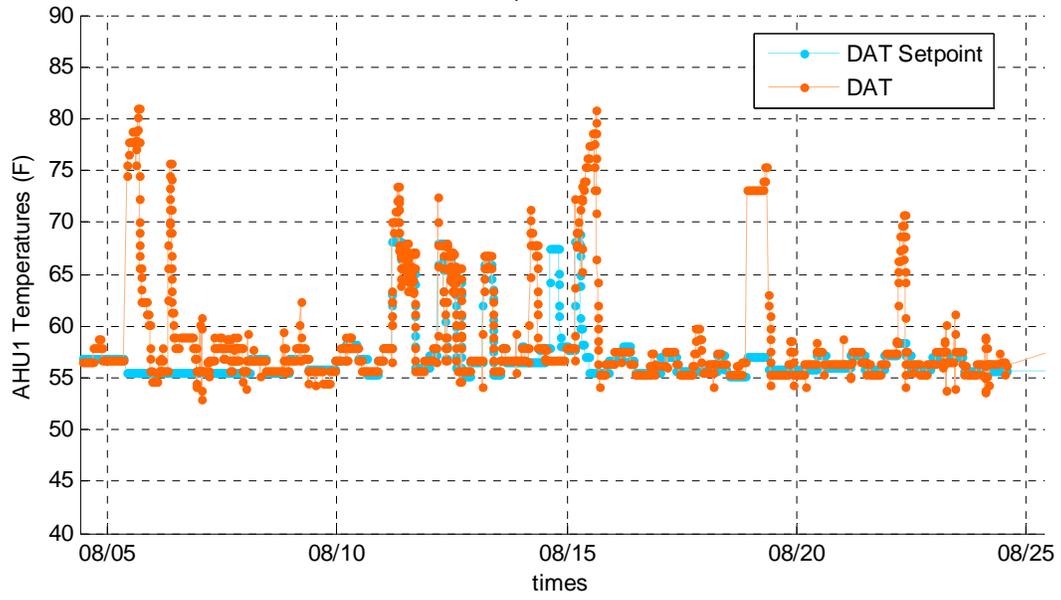


Figure 4.15 Building 7114 AHU1 Discharge air Temperature vs. Setpoint

## 5.0 PERFORMANCE RESULTS

### 5.1 SUMMARY OF PERFORMANCE OBJECTIVES AND OUTCOMES

Table 5.1 below provides the summary for evaluating the performance of the aBEMS demonstrated at Great Lakes.

Table 5.1 Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria <sup>15</sup>	Results
<b>Quantitative Performance Objectives</b>				
Reduce Building Energy Consumption (Energy) & Greenhouse Gas Emissions (CO <sub>2</sub> )	Building total electric consumption (kWh/ft <sup>2</sup> -yr) and peak demand (kW) Building total steam consumption (therm/ft <sup>2</sup> -yr) and peak demand Building total equivalent CO <sub>2</sub> emissions (kg)	Metering data for building electric and steam usage Building simulation data for equivalent CO <sub>2</sub> emissions	>20% reduction in building total energy consumption (over baseline) >15% reduction in building peak demand energy (over baseline) >20% reduction in building total equivalent CO <sub>2</sub> emissions (over baseline)	>20% reduction in building total energy consumption (over baseline) 7~15% reduction in building peak demand energy (over baseline) >20% reduction in building total equivalent CO <sub>2</sub> emissions (over baseline)
Reduce HVAC Equipment Specific Energy Consumption (Energy)	Chiller (kW/ton) Cooling Tower (gpm/ton, kW/ton) AHU (kW/ton) Fan (kW/CFM) Pump (kW/gpm)	Sub-metering data for HVAC equipment	>10% reduction in HVAC equipment energy consumption (over baseline)	5~15% reduction in HVAC equipment energy consumption for AHU, Fan (over baseline)
Reduce Building Loads (Energy)	Lighting loads (kWh) Plug loads (kWh)	Sub-metering data for lighting and plug loads	>10% reduction in lighting or plug loads (over baseline)	>20% reduction in lighting load (Drill Hall) with occupancy control
Building & HVAC System Reduced-order Model (ROM) Validation	Building load (kWh) Building overall energy consumption (kWh/ft <sup>2</sup> -yr) HVAC equipment energy consumption (kWh)	Simulation data from detailed building model (i.e., EnergyPlus) Metering data for building electric and steam usage Sub-metering data for lighting and plugs loads Building measured data	Predicted building loads difference (absolute error) between detailed model and ROM within +/- 10% Overall building energy consumption accuracy within +/- 15% (ROM vs. measurement) HVAC equipment energy consumption accuracy within +/- 10% at the rated	Predicted building loads difference (absolute error) between detailed model and ROM within +/- 10% Overall building energy consumption accuracy within +/- 15% (ROM vs. measurement) HVAC equipment energy consumption accuracy within +/- 10% at the rated

<sup>15</sup> Success criteria related to building and HVAC equipment energy consumption were assessed using both model-based simulations and actual energy measurements.

			conditions (ROM vs. measurement)	conditions (ROM vs. measurement)
Advanced Building Energy Management System Robustness	Percentage of faults classified correctly	Building energy fault identified/classified by advanced building energy management system	85% of faults identified are classified correctly (during 3-month demonstration period)	>95% of faults identified are classified correctly
Advanced Building Energy Management System Payback <sup>16</sup>	Simple payback time SIR (Savings-to-Investment Ratio)	Cost to install and implement advanced building energy management system Savings from using advanced building energy management system	Simple payback time is less than 5 years <sup>17</sup> SIR is greater than 1.25.	Simple payback time is less than 3 years SIR is greater than 2.5.
<b>Qualitative Performance Objectives</b>				
Ease of Use	Ability of an energy manager and/or facility team skilled in the area of building energy modeling and control to use the technology	Feedback from the energy manager and/or facility team on usability of the technology and time required to learn and use	With some training, An energy manager and/or facility team skilled in HVAC able to use the Advanced Building Energy Management System to identify and correct poor HVAC system performance	The user interface was refined based on feedback from facility team. The refined interface was well received.
Interactive and Visual Interface	Ability of an energy manager and/or facility team to effectively make building operation decision by using front-end user interface	Feedback from the energy manager and/or facility team on the interface	An energy manager and/or facility team able to more effectively exploit available building data to improve building operation decision-make	The user interface was refined based on feedback from facility team. The refined interface was well received.
Energy Fault Identification, Classification and Prioritization	Ability to detect, classify and prioritize (based on energy impact) building faults	Building measured data Building simulation data	Energy manager and/or facility team able to detect , classify and prioritize (based on energy impact) building faults by comparing simulated building performance (design intent or optimal) against measured	The system flags faulty behavior via anomaly scores. This information enables facility team to prioritize faults based on energy impacts from simulation models.

<sup>16</sup> This payback success criterion is only applied to the case when the only retrofits considered are those that do not involve major equipment retrofits

<sup>17</sup> DoD Energy Managers Handbook <http://www.wbdg.org/ccb/DOD/DOD4/dodemhb.pdf>

			building performance	
Energy Fault Corrective Action Prioritization	Ability to prioritize energy fault corrective actions based on energy impact	Building measured data Building simulation data	Energy manager and/or facility team able to prioritize energy fault corrective actions by comparing the simulated building energy impact benefits for each fault corrective action alternative against the simulated or measured baseline building energy performance	By comparing the simulated building energy impact benefits, the system enables facility team to prioritize the fault corrective action.
HVAC System Operation Strategies Prioritization	Ability to prioritize the alternative energy efficient HVAC system operation strategies	Building measured data Building simulation data	Energy manager and/or facility team able to prioritize energy efficient HVAC system operating strategies by comparing the simulated building energy impact benefits for each HVAC operation strategy against the simulated or measured baseline building energy performance	Energy manager and/or facility team able to prioritize energy efficient HVAC system operating strategies by comparing the simulated building energy impact benefits for each HVAC operation strategy against the simulated or measured baseline building energy performance
Scalability	Ability of advanced building energy management system to be scaled to different types and sizes of buildings Time to implement the system for a new building	Feedback from the energy manager and/or facility team on scalability; Implementation time for Drill Hall; Implementation time for Building 7113/7114	Type of building: successful demonstrations for office and barracks buildings; Size of building: scale from Drill Hall with smaller floor area to building 7113/7114 with bigger floor area; Implementation time is about 30% less for building 7113/7114 compared with Drill Hall	The aBEMS was successful implemented in Buildings with different type and different size (Building 7230: drill hall and office building with 70,000 ft <sup>2</sup> vs. Building 7113/7114: barracks building with 300,000 ft <sup>2</sup> ).

## 5.2 PERFORMANCE RESULTS DISCUSSION

Each performance objective presented in Table 5.1 is described in the following paragraphs. Additional details about the performance assessment can be found in Appendix A.

### Quantitative Performance Objectives

#### 1. *Reduce Building Energy Consumption (Energy) & Greenhouse Gas Emissions (CO<sub>2</sub>).*

Purpose: The ultimate goal of the aBEMS is to reduce energy consumption, peak electric demand, and greenhouse gas emissions in DoD facilities by providing actionable information to facility managers and building operators. This objective is to reduce building total energy consumption including HVAC, lighting and equipment (i.e., plug loads). For example, turning off lights when the space is unoccupied will reduce total building electricity consumption significantly. To achieve 20% energy savings at the building level, 10% savings is achieved by visualizing energy diagnostics and an additional 10% energy savings is achieved through alternative energy system operation strategies.

Metrics and Success Criteria: The metrics used to assess this objective and the success criteria are listed as following:

- Total electric consumption (kWh/(ft<sup>2</sup>-year)): 20% reduction over the baseline (10% energy savings by visualizing energy diagnostics and an additional 10% energy savings through alternative energy operation strategies)
- Peak electric demand (kW): 15% reduction over the baseline
- Total steam consumptions (therm/(ft<sup>2</sup>-year)): 20% reduction over the baseline
- Peak steam demand : 15% reduction over the baseline
- Total equivalent carbon dioxide (CO<sub>2</sub>) emissions (kg): 20% reduction over the baseline

Data: The above metrics were assessed with model based simulations and actual building energy consumption measurement. The baseline building is the current as-built building without any energy fault corrective actions. The data required to calculate these energy-related metrics are either simulation data or metering data for building electric, hot water, chilled water and steam usage. The simulation data was used for calculation of equivalent CO<sub>2</sub> emissions.

Analytical Methodology: Quantitative comparisons were performed: 1) between measured data from current as-built building and the building with faults corrected and/or 2) between predictions from different operation strategies based on a calibrated building ROM.

Results: The following faults were detected and diagnosed at the demonstrated sites: Building 7230 (Drill Hall) and Building 7113/7114.

- Economizer faults: Approximately 2,000 CFM more outside air intake during non-economizer modes (Building 7230)
- Lighting faults: lights on during unoccupied hours (Building 7230)
- Economizer faults: The control sequence of operation was incorrect due to errors in the enthalpy calculations. This caused significantly more outside air intake during hot summer days (e.g., 100% vs. minimal outside air intake) (Building 7113/7114).
- Economizer faults: Outside air fraction was not minimal in the heating mode (Building 7113/7114).
- Absorption chiller issues: Chiller 1 was turned off due to operational issues during the whole demonstration period. Chiller 2 had issues related to a leaky steam pipe and,

steam valve oscillation. Chilled water temperature setpoints could not be maintained during hot summer days, consequently, the AHU supply temperature setpoints and room temperature setpoints could not be maintained (Building 7113/7114)

As an example, Figure 5.1 below shows the measured chilled water consumption vs. outside air temperatures for July (with faults) and August (faults corrected) in Building 7114. The chilled water BTU meter measurement confirmed 18% chilled water consumption reduction due to the corrected economizer faults. Details for the energy faults diagnostics and savings calculations can be found in Appendices A.4 and A.5

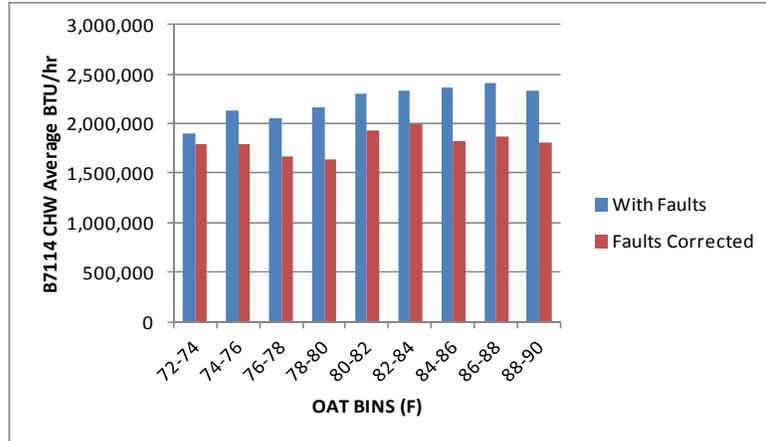


Figure 5.1 Measured Chilled Water Consumption Comparisons (with Faults vs. Faults corrected)

The following HVAC operation strategies were evaluated using the integrated ROM:

- Pre-cooling and pre-heating (Building 7230)
- Chilled water supply temperature (CHWT) setpoint reset (Building 7230)
- Zone temperature setpoint reset (Building 7113/7114)
- Out air fraction optimal control (Building 7113/7114)

Table 5.2 below shows the operation sensitivity results for Building 7230. More details about the HVAC operation sensitivity study assessment can be found in Appendix A.3.

Table 5.2 Results of Sensitivity Study for Cooling Season in Building 7230

Energy Savings in July 2010	Pre-cooling Savings	Pre-cooling and CHWT Setpoint Reset Savings
Chiller Electricity	15.4%	18.1%
Whole Building Level Electricity	7.2%	8.2%
Peak Demand	12.5%	14.7%

The summary of the identified savings and related payback for Building 7113/7114 is provided in Table 5.3. Details for the performance assessment in terms of savings calculations can be found from Appendix A.5.

It is assumed that the equivalent carbon dioxide (CO<sub>2</sub>) emissions reduction is proportional to energy consumption reduction.

Table 5.3 Summary of Selected Savings Opportunities for Building 7113/7114

Selected energy savings strategies	Energy Savings (%) compared with current operation	Annual savings in \$ <sup>a</sup>	Simple payback <sup>b</sup>
Economizer faults (enthalpy calculation )	18% (chilled water consumption <sup>c</sup> )	\$12,950	No capital cost
Zone temperature daytime setpoint reset (from 70°F to 74°F) in the cooling season	16% (B7113) 18% (B7114)	\$52,734 <sup>d</sup>	No capital cost
Zone temperature daytime setpoint reset (from 72°F to 68°F) in the heating season	11% (B7113) 15% (B7114)		
Zone temperature daytime setpoint reset together with outside air control in the cooling season	24% (B7113) 12% (B7114)		
Zone temperature daytime setpoint reset together with outside air control in the heating season	23% (B7113) 39% (B7114)		

- a) Assume 1) \$0.069 per kWh for the electricity; 2) \$8.7 per MMBTU for the steam; 3) Use 2011 utility bill for the baseline energy consumption.  
b) Only consider the capital cost required to implement these energy savings strategies.  
c) Measured savings based on BTU meter data from July 2011 to August 2011.  
d) Assume 20% HVAC related energy savings (electricity and steam) at the campus level (the rationale is provided in Appendix A.5).

2. *Reduce HVAC Equipment Specific Energy Consumption.*

Purpose: Energy consumption reduction was also evaluated at the HVAC equipment level.  
Metrics and Success Criteria: The following metrics and criteria were selected for the evaluation of individual equipment performance:

- Chiller (kW/ton): 10% reduction over the baseline
- Air handling unit – AHU (kW/ton): 10% reduction over the baseline
- Fan (kW/CFM): 10% reduction over the baseline
- Pump (kW/GPM): 10% reduction over the baseline
- Cooling tower (GPM/ton, kW/ton): 10% reduction over the baseline

Data: These metrics were assessed with HVAC equipment power sub-metering data and measurement of HVAC equipment airflow rates (fans) and water flow rates (pumps).

Analytical Methodology: Quantitative comparisons were performed: 1) between measured data from current as-built building and the building with faults corrected and/or 2) between predictions from different operation strategies based on a calibrated building ROM.

Results: The HVAC operation sensitivity study shows that the air-cooled chiller performance was improved by 5-10% in the terms of kW/ton. Fan electricity consumption was reduced by 10 ~ 11%. Due to issues with the chiller plant in Building 7113/7114 (See Appendix A.1 for details), the Building 7113/7114 absorption chiller performance optimization was not included in the demonstration.

### 3. *Reduce Building Loads (Energy).*

Purpose: Reducing building loads (e.g. lighting, plug) is an effective way to reduce building demand energy. It is quite common to find lighting and other equipment operating when it is unnecessary (e.g., lights on during unoccupied hours). The aBEMS was able to automatically detect this type of fault.

Metrics and Success Criteria: The following metric and criteria were used to assess this performance objective:

- Lighting or plug loads (kWh): 10% reduction over the baseline

Data: Sub-metering data for lighting and plug loads (electric equipment such as computers and printers) was used to assess the reduction in energy use (kWh)

Analytical Methodology: Quantitative comparisons were performed between predictions from different operation strategies based on a calibrated building ROM.

Results: Lights in Building 7230 were on during unoccupied hours. Based on a calibrated building model, the electricity consumption at the building level could be reduced by 23% if occupancy based light control was implemented in Building 7230.

### 4. *Building & HVAC System Reduced-order Model (ROM) Validation.*

Purpose: One featured innovation from the aBEMS is that it employs an integrated, reduced-order model for a whole building. This model provides hourly calculations of building energy consumption, HVAC, and lighting systems performance, taking into account the dynamic interactions among the building envelope, airflow, weather, internal loads, building usage, equipment, and controls. The performance generated by this physics-based reference model, which represents “design intent” or ideal performance, is compared with measured data from the building. The performance deviation will indicate sub-optimal operation or faults. The ROM was also used for the HVAC operation sensitivity analysis. The data generated from the ROM was used as the baseline for the FDD module.

Metrics and Success Criteria: The following metrics and criteria were used to evaluate building model accuracy:

- Building load (kWh): Predicted building load difference (absolute error) between a detailed model (i.e., EnergyPlus model) and a ROM within  $\pm 10\%$ .
- Building overall energy consumption (kWh/(ft<sup>2</sup>-yr)): Accuracy within  $\pm 15\%$  compared with real data.
- HVAC equipment energy consumption (kWh): Accuracy within  $\pm 10\%$  compared with real data at rated conditions.

Data: Measured data was used to validate the building reference model. The measured data include metering data for building electric and steam usage, and sub-metering data for HVAC equipment. Historical utility bills were also used for model validation. The outputs from EnergyPlus such as building thermal loads at different levels (e.g., zonal and building levels) were used to validate the building reference ROM.

Analytical Methodology: Quantitative comparisons were performed: 1) between predictions from a detailed model (i.e., EnergyPlus model) and a ROM, and 2) between measurements and predictions from a ROM. The building reference ROM performance predictions differed from the actual building performance measurements. However, given that this ROM contains a representation of the actual physics in the building, it can be used to assess the relative differences in building performance due to incremental building changes (e.g., control set-points, equipment faults). Therefore, while the overall absolute performance accuracy of the model may be  $\pm 15\%$ , the model can be used to assess the performance impact of incremental changes relative to a baseline, calibrated model configuration. Essentially, the relative model uncertainty for these building incremental changes is significantly lower than the absolute model accuracy. This allows the impact on the project performance objectives to be assessed using the building reference models.

Results: Extensive validation has been performed for the reduced-order models in terms of load predictions from the building envelope ROM and energy performance predictions from the HVAC equipment ROM and the integrated system ROM. Appendices A.1 to A.2 provide detailed information about the validation results. Table 5.4 shows the comparisons between annual and peak loads predictions from the detailed building performance model (EnergyPlus) and the ROM.

Table 5.4 Annual and Peak Loads Comparisons between the EnergyPlus and the ROM for Building 7230

Loads (building level)	EnergyPlus	ROM	error*
Annual cooling (MW-hr)	169.3	174.7	3.18 %
Peak cooling (kW)	140.6	144.4	2.72 %
Annual heating (MW-hr)	96.1	106.7	10.98 %
Peak heating (kW)	174.2	162.6	6.67 %

\* The error is computed relative the predictions of the EnergyPlus model

Figure 5.2 shows HVAC equipment model validation results for Building 7113/7114. Figures 5.3 and 5.4 illustrate the validation results with measurements for an integrated system ROM of Building 7230 and Building 7114. It is observed that the model accuracy is worse when low load conditions existed. In addition, measurements with low load conditions (e.g., middle of the night) had some spikes due to transient behaviors of building thermal loads. However, the energy impacts at low load conditions most time are negligible. For example, considering a typical summer day in Building 7114, the HVAC electricity consumption from 12:00am to 4:00am is less than 5% of total daily electricity consumption. And the chilled water consumption from 12:00am to 4:00am is less than 10% of total daily chilled water consumption.

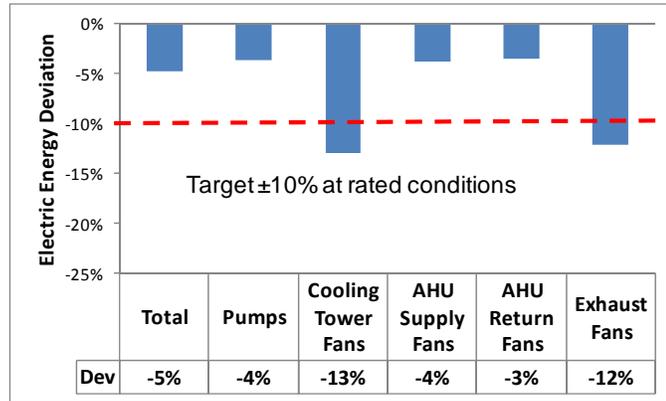


Figure 5.2 Electric Energy Deviation Errors for HVAC Components Models in Building 7113/7114

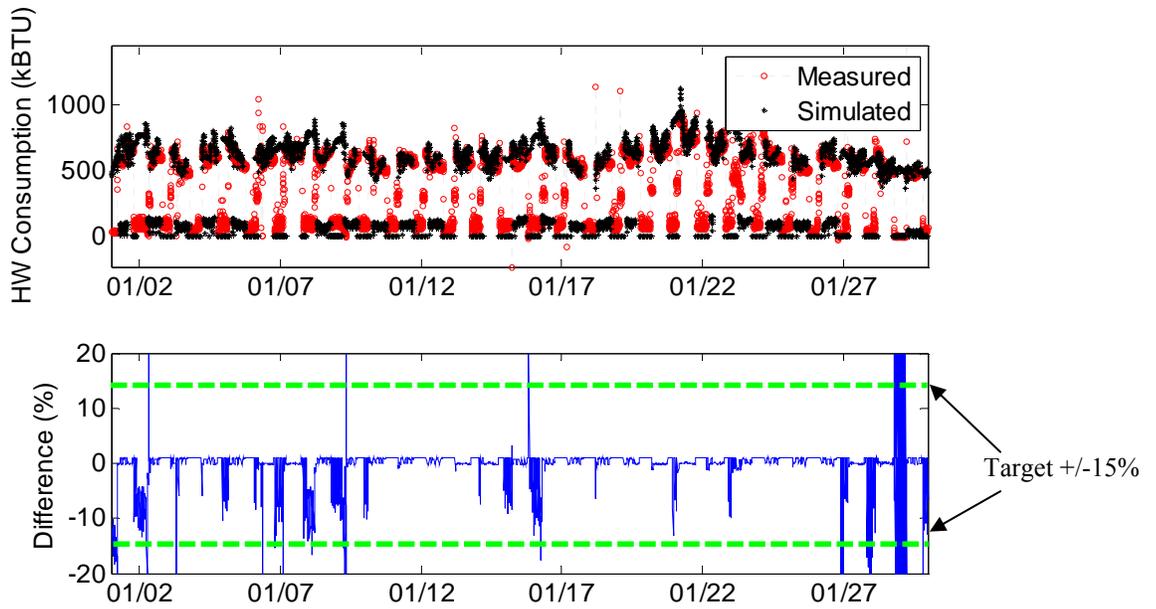


Figure 5.3 Comparisons of Hot Water Energy Consumption between Predictions from a ROM and Measurements in January, 2011 for Building 7230

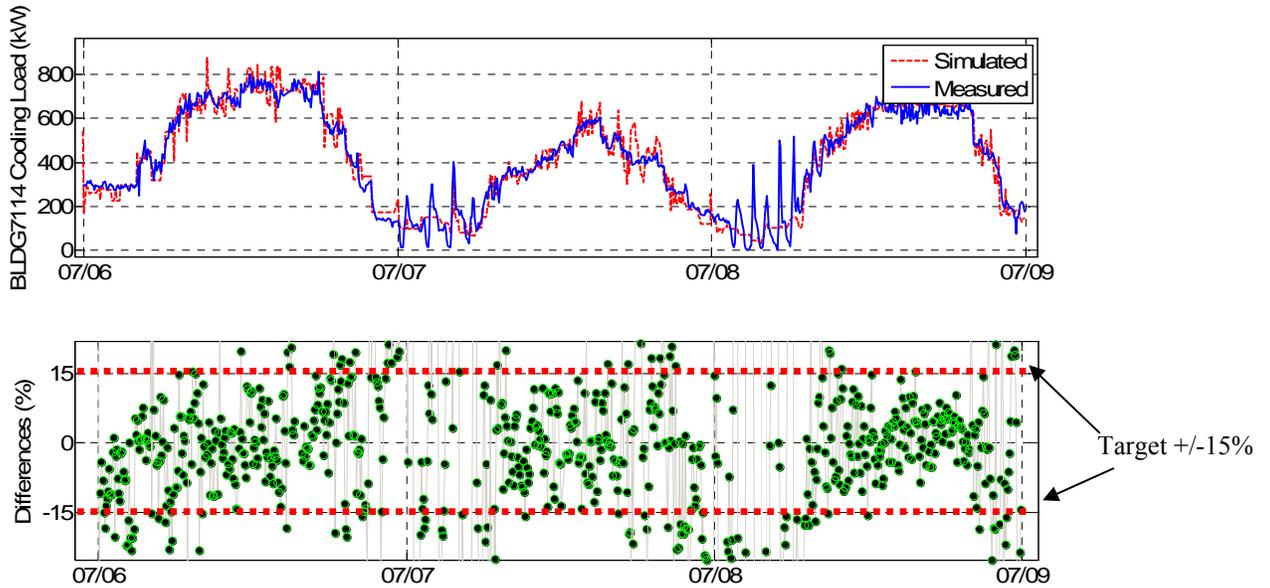


Figure 5.4 Cooling Season Integrated Model Validation from 07/06/2011 to 07/10/2011 for Building 7114

In summary, the total building load comparisons show that the differences between measurements and predictions for the integrated ROM are within the  $\pm 15\%$  target for the majority of time (as shown in Figure 5.5). The model prediction errors are outside the  $\pm 15\%$  error band when there are low load conditions. This is as expected because the HVAC ROM performance is degrading at non-rated conditions.

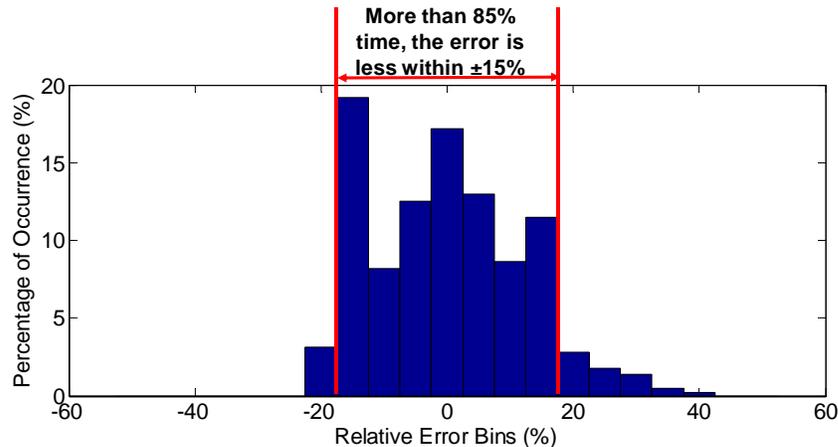


Figure 5.5 Model Error Distribution for Cooling Season Integrated Model Validation from 7/06/2011 to 07/10/2011 for Building 7114

5. *Advanced Building Energy Management System Robustness.*

Purpose: It is critical for the success of this project that the aBEMS should be able to identify and classify building faults correctly.

Metrics and Success Criteria: During the demonstration period, it is expected that 85% of the faults identified by the aBEMS system will be classified in line with the building facility manager and/or the team assessment of fault causes.

Data: Building energy faults identified/classified by the advanced building energy management system and the assessments from the building experts (e.g., building facility manager)

Analytical Methodology: To quantify the accuracy of the diagnostics algorithm, a dataset with known faults (*a priori*) is needed. The algorithms can be then applied to the dataset to quantify how many of the known faults were detected correctly.

Results: The data from the AHU1 economizer in Building 7114 during March 1 -31, 2012 was chosen. It was assumed (confirmed with the faculty team) that the outside air damper should operate at the minimal opening position whenever the AHU is in the heating mode (i.e., heating valve is open and hot water pump is ON). If the damper is not at the minimal position, then a fault is occurring and should be detected. The confusion matrix (e.g., matrix of fault classification accuracy) in Table 5.5 shows the numbers of accurate classifications, missed detections and false alarms for this fault. This matrix contains information about actual and predicted classifications done by the FDD method. True anomalies were detected correctly 2740 times out of 2843 actual anomalies corresponding to an accuracy of 96.38%. No fault condition was detected correctly 612 times out of 781 times (78.36%). The false alarm rate was 21.64% and missed detection rate was 3.62%.

Table 5.5 Confusion Matrix for Fault Classification Accuracy

	TRUE	FALSE	Total
TRUE	2740	103	2843
FALSE	169	612	781
Total	2909	715	3624

Details about this confusion matrix can be found in Appendix A.4.

6. *Advanced Building Energy Management System Payback Time.*

Purpose: Simple Payback (SPB) and SIR (savings-to-investment ratio) were used as metrics to assess the economic viability of the aBEMS.

Metrics and Success Criteria: The following criteria were used to evaluate the advanced building energy management system

- SPB: less than 5 years. DoD Energy Mangers Handbook [19] recommends that all projects with 10 year or less simple payback that fit within financial constraints shall be implemented.
- SIR: greater than 1.25. An investment is cost effective if its SIR is greater than 1.0. Under DoD funding programs, SIR is typically required to be 1.25 or higher [19].

Data: Cost to install and implement the advanced building energy management system.

Savings from using advanced building energy management system for the demonstration sites.

Analytical Methodology: The MILCON ECIP template in the NIST BLCC program [20] was used to calculate the SPB (Simple Payback) and SIR (Savings to Investment Ratio) for the aBEMS deployed at the demonstration sites. A practical SIR formula for building related projects, recommended by NIST [20], was used in this project:

$$SIR_{A:BC} = \frac{\Delta E + \Delta W + \Delta OM\&R}{\Delta I_0 + \Delta Repl - \Delta Res} \quad (1)$$

Where:

$SIR_{A:BC}$  : Ratio of operational savings to investment-related additional costs, computed for the alternative relative to the base case;

$\Delta E = (E_{BC} - E_A)$ : Savings in energy costs attributable to the alternative;

$\Delta W = (W_{BC} - W_A)$ : Savings in water costs attributable to the alternative;

$\Delta OM\&R = (OM\&R_{BC} - OM\&R_A)$ : Difference in OM&R costs;

$\Delta I_0 = (I_A - I_{BC})$ : Additional initial investment cost required for the alternative relative to the base case;

$\Delta Repl = (Repl_A - Repl_{BC})$ : Difference in capital replacement costs;

$\Delta Res = (Res_A - Res_{BC})$ : Difference in residual value.

All amounts in Equation (1) are in present values.

If  $\Delta E_t$ ,  $\Delta W_t$ ,  $\Delta OM\&R_t$  are assumed to be the same in every year (i.e., there is no price escalation and quantities of energy and water saved each year are the same) and there are no additional non-annually recurring OM&R or replacement costs, the following simplified formula can be used to compute simple payback time (SPB)[20]:

$$SPB = \frac{\Delta I_0}{[\Delta E_0 + \Delta W_0 + \Delta OM\&R_0]} \quad (2)$$

Where:

$\Delta I_0$  : Additional initial investment cost;

$\Delta E_0$  : Annual savings in energy cost;

$\Delta W_0$  : Annual savings in water cost;

$\Delta OM\&R_0$  : Annual difference in OM&R costs.

Results: Tables 6.5 and Table 6.6 in Section 6.2 summarize the cost analysis results for the Building 7113/7114 demonstration. Details about this cost analysis can be found in Section 6.2 and Appendix B. In summary, with current initial costs of \$150,129 and HVAC related energy savings of 20%, the SPB for the advanced building energy management system in Building 7113/7114 is 2.85 years and the SIR is 2.78.

## Qualitative Performance Objectives

### 1. Ease of Use.

Purpose and Metrics: The aBEMS should be an easy of use tool with an interactive interface for building facility managers and operators. The potential users of this aBEMS tool include the building energy manager and/or facility team who are skilled in the area of building HVAC systems (e.g., building energy modeling and controls). With some training, they should able to use the aBEMS to identify and correct poor HVAC system performance

Results: The feedback from Great Lakes facility team on the usability of the technology and time required to learn and use the aBEMS system was used to help the project team to develop, evaluate, and refine the aBEMS. The refined interface was well received.

### 2. Interactive and Visual Interface.

Purpose and Metrics: The aBEMS should provide an interactive and visual interface for facility managers and building operators to facilitate them to effectively make building operation decision.

Results: The feedback from these users on the interface was used to help the project team to develop, evaluate, and refine the interface. The user interface was refined based on feedback from Great Lakes facility team and the refined interface was well received.

3. *Energy Fault Identification, Classification and Prioritization.*

Purpose and Metrics: The aBEMS should be able to detect, classify and prioritize building faults based on energy impact.

Results: The aBEMS enabled the energy manager and/or facility team to detect, classify, and prioritize building energy system faults based on energy impact by comparing simulated building performance (design intent or optimal) against measured building performance. The aBEMS automatically identified whole building performance deviations from the reference reduced-order model by using probabilistic graphical network models, cluster analysis and domain expertise. This enabled root cause analysis of these deviations, not only identification of a pre-defined, rule-based, set of equipment faults. It also provided a means to prioritize the faults based on energy impact. The data required to evaluate this metric was obtained from measurement and simulation.

4. *Energy Fault Corrective Action Prioritization.*

Purpose and Metrics: The aBEMS should be able to prioritize energy fault corrective actions based on energy impact.

Results: The aBEMS enabled the energy manager and/or facility team to prioritize energy fault corrective actions by comparing the simulated building energy impact benefits for each fault corrective action against the simulated or measured baseline building energy performance. The physics-based, calibrated reduced-order models were used to evaluate the energy and economic value of alternative correction actions. The data required to evaluate this metric was obtained from measurements and simulation.

5. *HVAC System Operation Strategies Prioritization.*

Purpose and Metrics: The aBEM should be able to prioritize the alternative energy efficient HVAC system operation strategies.

Results: The aBEMS enabled the energy manager and/or facility team to prioritize energy efficient HVAC system operating strategies by comparing the simulated building energy impact benefits for each HVAC operation strategy against the simulated or measured baseline building energy performance. The data required to evaluate this metric was obtained from measurements and simulation.

## 6.0 COST ASSESSMENT

A cost model for the Advanced Building Energy Management System ( aBEMS) is provided in Table 6.1. A detailed discussion is given in the following subsections.

**Table 6.1 Cost Model aBEMS**

Cost Element	Data Tracked During the Demonstration	Estimated Costs (\$)
<b>Hardware capital costs</b>	Estimates made based on component costs for demonstration	\$70,919
<b>Installation costs</b>	Labor and material required to install	\$79,210
<b>Consumables</b>	Estimates based on rate of consumable use during the field demonstration	N/A
<b>Facility operational costs</b>	Reduction in energy required vs. baseline data	N/A
<b>Maintenance</b>	<ul style="list-style-type: none"> <li>• Frequency of required maintenance</li> <li>• Labor and material per maintenance action</li> </ul>	One day per year (\$1,000)
<b>Hardware lifetime</b>	Estimate based on components degradation during demonstration	0
<b>Operator training</b>	Estimate of training costs	One day (\$1,000)

<sup>1</sup> Detailed list of materials and analytical costs provided in Sections 6.1 and 6.2

## 6.1 COST DRIVERS

### Hardware Capital Cost

The hardware capital costs are mainly attributed to the additional instrumentation, which is required to provide run-time model inputs, calibrate models and do energy performance diagnostics. A BMS with BACnet gateway is a requirement for implementing the technology. In cases where the BACnet gateway is absent and needs to be provided, additional cost is incurred. The measurements related to run-time weather inputs are outdoor dry bulb temperature, outdoor relative humidity, direct normal solar radiation, diffuse solar radiation, wind speed and direction. The additional measurements required to track key performance metrics are electrical power sub-metering and thermal energy consumption for cooling and heating. The sub-metering of the electrical power should be able to measure the whole building electrical power and separate the lighting electrical power, plug load electrical power, key HVAC equipment (e.g., chiller) and total HVAC equipment electrical power.

The detailed breakdown costs for materials used for the demonstration are listed in Table 6.2 for Building 7113/7114. Existing instrumentation from ESTCP EW-0929 [16] was used for Building 7230 with additional chilled water BTU meters at the AHU level.

Table 6.2 Materials Cost for Building 7113/7114 Instrumentation

Items	Cost	Percentage
8 BTU meters	\$39,144	55%
10 DEMs (Digital Energy Monitor)	\$12,738	18%
2 steam condensate meters	\$2,455	3%
BACnet server	\$5,500	8%
Wireless solution for weather station	\$6,500	9%
PC	\$4,582	6%
Total	\$70,919	

Table 6.3 Labor Cost for Building 7113/7114 Instrumentation

Items	Cost	Percentage
8 BTU meters	\$34,250	43%
10 DEMs (Digital Energy Monitor)	\$19,175	24%
2 steam condensate meters	\$6,895	9%
BACnet server	\$9,510	12%
Wireless solution for weather station	\$9,380	12%
PC	NA	
Total	\$79,210	

Table 6.3 lists the labor cost breakdowns for instrumentation. The labor cost covers sensor/meter installation and points mapping within Siemens BMS.

### Weather Station and Real Time Weather Data

Real time weather data from an on-site weather station, including solar radiation data, are essential to reduce model prediction error. Statistical TMY3 weather data can cause the model predictions to significantly deviate from measured data. For the July 2010, the average difference between measured outside air temperature and TMY3 data is about 5.4°F (3°C), and maximum difference is about 23°F (12.75°C). When deploying the technology, there are a few options that can be considered for cost reduction:

- 1) If internet access is available, the data from the NOAA website (National Oceanic and Atmospheric Administration) could be used directly without installing the weather station. If internet access is not available, as is the case at Naval Station Great Lakes, then a weather station has to be installed to access real time weather data.
- 2) Multiple buildings on one campus are able to share one weather station with the necessary network setup to reduce the cost per building. It is possible that this kind of network setup (e.g., a centralized BMS) is not available for some campuses.

Building 7113/7114 is only about 100 feet away from Building 7230 which has an on-site weather station installed (ESTP EW-0929). Unfortunately, the BMS networks from these two buildings cannot communicate with each other due to a Navy IT security policy. To reduce the cost, a wireless sub-network was created to acquire and transfer the weather information directly from the existing weather station in Building 7230 to the BMS network in Building 7113/7114. Table 6.4 compares the cost for two options. The total cost was reduced by more than 50% with a wireless solution.

Table 6.4 Comparisons of two options for weather station

	<b>Materials</b>	<b>Labor</b>	<b>Total</b>
<b>Wireless Solution</b>	\$6,500	\$9,380	\$15,880
<b>New Weather Station</b>	\$21,990	\$10,695	\$32,685

### **Additional Sub-metering**

The cost associated with the sub-metering is site-specific and presents the highest variable cost. The number of electric power meters needed to disaggregate depends on the layout of electrical circuits. The end-uses can be as few as four or greater than ten. The number of electric power meters needs to be determined by reviewing the electrical as-built drawings and through an on-site audit.

The instrumentation for thermal energy measurement needs to be determined on a site-by-site basis, e.g., electromagnetic vs. turbine flow meter, hot water measurement vs. steam measurement. If long straight pipe sections are available, a more cost effective turbine flow meter will be sufficient. Otherwise, a magnetic flow meter is required.

If district heating or cooling is present, the need for chiller electric power measurement and boiler fuel measurement can be eliminated if the focus is at the building level.

### **Other Costs**

A dedicated computer to host the software needed by the aBEMS is required. Most commercial available computers are adequate. A BACnet gateway is required only if the existing BMS is not BACnet compatible.

Several site-specific characteristics that will significantly impact cost are highlighted here:

- **Networking capability for campus applications.** If networking is available to allow multi-building sharing of a weather station, then only one weather station is needed.
- **Electrical system layout.** A good electrical system design requires significantly fewer electric power meters to disaggregate the end-uses.
- **Cooling and heating distribution system.** If long straight main pipe segments are not available, then multiple BTU meters will need to be installed on the piping branches to obtain the total thermal energy consumption.

## **6.2 COST ANALYSIS AND COMPARISON**

The MILCON ECIP template in the NIST BLCC program [20] is used to calculate the SPB (Simple Payback) and SIR (Savings to Investment Ratio) for the aBEMS in Building 7113/7114.

Section 5 and Appendices A.3, A.4 and A.5 provide details of savings opportunities from the demonstration buildings. It is shown that annual energy savings of \$52,734 could be achieved for electricity and steam for Building 7113 and 7114. It is assumed that there will be ~\$1,000 savings per year per building for operation and maintenance costs due to the fact that the system down-time could be reduced and the facility team could better prioritize their work orders. The following assumptions are used:

- \$0.069/kWh for electricity and \$8.7 /MMBTU for steam

- No demand charge
- Real discount rate of 3%
- Inflation rate of 1.2%
- Length of study period is 10 years

A few different capital cost scenarios (Table 6.5 for Building 7113/7114) were proposed after the analysis of the current capital cost structure. Figure 6.1 illustrates the capital cost structure for Building 7113/7114. The materials (i.e., sensors and meters) and installation costs are highly dependent on the specific site and buildings (e.g., system configuration and roof access requirement etc.). Therefore, it is reasonable to assume different capital cost scenarios.

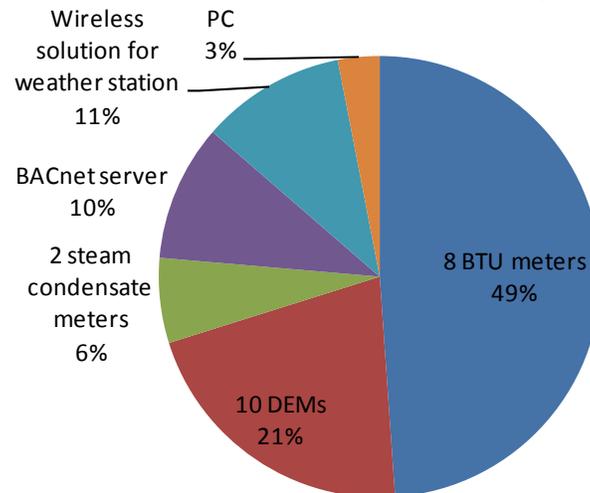


Figure 6.1 Pie chart of capital cost structure for Building 7113/7114

The following assumptions are used for different capital cost scenarios:

- If the building has a native BACnet BMS, then BACnet server will not be needed.
- If there is a personal computer (PC) available, then a PC will not be needed.
- If the weather information can be accessed from the internet or an existing weather station on the base via the BMS network, then the cost related to weather station (e.g., wireless solution for Building 7113/7114) will be eliminated.
- The installation cost reduction is linearly related to the material cost reduction.
- To effectively use the advanced building energy management system, sub-metering is necessary. The lighting faults (Building 7230) could not have been identified without the sub-meters installed in this project. New emerging technology for electrical sub-meters (about \$250 per point including materials and installation) could be leveraged.

The SPB and SIR in different capital cost scenarios for the advanced building energy management system demonstrated in the Great Lakes buildings are summarized in Table 6.6 below.

Table 6.5 Capital Cost Scenarios for Building 7113/7114

Scenario 1 Full capital cost (\$ 150,129)	Scenario 2 87% of capital cost (\$ 130,537)	Scenario 3 76% of capital cost (\$ 114,657)	Scenario 4 57% of capital cost (\$ 85,244)
<ul style="list-style-type: none"> <li>• BACnet server</li> <li>• 10 DEM</li> <li>• 8 BTU meters</li> <li>• 2 steam condensate meter</li> <li>• PC</li> <li>• Weather station (wireless solution)</li> </ul>	<ul style="list-style-type: none"> <li>• 10 DEM</li> <li>• 8 BTU meters</li> <li>• 2 steam condensate meter</li> <li>• Weather station (wireless solution)</li> </ul> <p><b>Remove BACnet server and PC</b></p>	<ul style="list-style-type: none"> <li>• 10 DEM</li> <li>• 8 BTU meters</li> <li>• 2 steam condensate meter</li> </ul> <p><b>Remove BACnet server, PC and weather station</b></p>	<ul style="list-style-type: none"> <li>• 10 low cost electrical sub-meters</li> <li>• 8 BTU meters</li> <li>• 2 steam condensate meter</li> </ul> <p><b>Remove BACnet server, PC and weather station</b> <b>Replace DEMs with new emerging sensors</b></p>

Table 6.6 Cost Analysis Results for Building 7113/7714 Demonstration

	Scenario 1 Capital cost	Scenario 2 87% of capital cost	Scenario 3 76% of capital cost	Scenario 4 57% of capital cost
First year savings <sup>18</sup> :	\$52,734	\$52,734	\$52,734	\$52,734
Simple Payback Period (in years): SPB	2.85	2.48	2.17	1.62
Savings to Investment Ratio: SIR	2.78	3.20	3.64	4.9

Performance objectives were for less than 5 years for SPB and greater than 1.25 for SIR. As shown in Table 6.6, both objectives were achieved for the advanced building energy management system deployed in Building 7113/7114 including Scenario 1 (i.e., full capital cost as spent in this demonstration). The return on investment analysis depends on the baseline energy consumption for a given building. The Energy Usage Index (EUI) for Building 7113/7114 was 176.75 KBTU/sf<sup>2</sup>-year in 2009.

Currently, some of the faults identified in Building 7113/7714 are related to thermal comfort rather than energy consumption. For example, due to control/chiller problems, there were times when the chiller was actually switched off when it was commanded on, so the building consumed less energy than expected but the room temperatures were not maintained. The economic impact from occupant productivity due to lower thermal comfort is not quantified here as it is beyond the scope of this project. Based on an ASHRAE study [21] on the life cycle of a building, initial construction cost is about 2% and operational and energy cost is about 6%, while occupancy cost accounts for about 92%. The aBEMS is able to identify issues related to thermal comfort to help address productivity problems.

<sup>18</sup> Section 5 and Appendices A.3, A.4 and A.5 provide details of savings opportunities from the demonstration buildings.

## 7.0 IMPLEMENTATION ISSUES

This section includes a discussion of the implementation issues in the areas of instrumentation, modeling, BMS integration, network communication, user interfaces and required skills issues.

### **Instrumentation**

All instrumentation used in this demonstration is standard Commercial Off-the-shelf (COTs) products. The recommended measurement accuracies for the power meters and thermal meters are given in *A Specifications Guide for Performance Monitoring Systems* [22]. If the BMS is not a 'native' BACnet system, a BACnet gateway will be required to implement the technology. Care is needed when setting up the BACnet gateway. The change of value (COV) for updating the measurement for the weather station, power meters and thermal meters should be as small as possible while not overloading the data communication network. Currently, the instrumentation cost is relatively high. The largest components are the equipment and installation costs related to sub-metering and the on-site weather station. It is possible to eliminate the on-site weather station by using weather data from the internet or an existing weather station on the base.

The cost drivers for the building energy monitoring system include: material and installation costs for thermal and electrical energy meters, commissioning costs associated with mapping hardware points into the building energy management systems, and commissioning costs related to the quality of energy monitoring data. A low cost and scalable building energy monitoring system should be on the DoD demonstration agenda. This system should aim to reduce costs related to the energy monitoring system necessary to enable advanced Building Energy Management Systems that integrate performance monitoring, energy diagnostics and control technologies capable of delivering and maintaining 30% energy saving opportunities and reducing facility maintenance labor costs and improve occupant productivity. The following key technologies need to be addressed:

- A comprehensive design guideline to determine the minimum set of sensors for deploying energy monitoring systems in DoD buildings;
- Virtual sensors derived from physical based models;
- Low cost, scalable building electrical and thermal energy sub-metering;
- Middleware that provides seamless data acquisition and automated point mapping into the advanced building energy management systems;
- Automated sensor health monitoring that combines heuristic rules, physical based models and data mining algorithms.

### **Modeling**

Matlab was used in this project as the platform for simulation and visualization. For a technology demonstration project, the use of Matlab is appropriate. For broader deployment, existing Matlab code can be compiled and distributed as an executable program. In other words, the aBEMS can be deployed on computers without Matlab. The Matlab-based visualization is available only on the local machine. The next generation system would utilize a web-based visualization tool.

For some equipment models, including absorption chiller and cooling coil, lack of good quality data created some issues for model calibration and validation. Currently, considerable time is

spent dealing with issues related to sensor data quality (e.g., sensor bias and drifting) for modeling and diagnostics. Real-time sensor health monitoring provides a means to dramatically reduce the cost related to the commissioning of energy monitoring systems to ensure data quality. An automated sensor health monitoring system should be considered. This system combines physics-based models, heuristic rules and machine learning algorithms.

Also, information related to building current control sequences was not totally open due to a proprietary BMS on site. There is a need for a robust, scalable and standardized way to collect and store both static and dynamic operation data throughout a building lifecycle.

### **BMS Integration**

In this demonstration project, real time building operational data was collected through a BACnet gateway by using the open source software BCVTB<sup>19</sup>. A Building Information Model (BIM) supported database was prototyped and used to store both building static data (e.g. model parameters, HVAC configuration, etc) and building dynamic operational data (e.g., temperature, energy). All the mapping was done manually which increased the implementation cost. The following gaps are identified:

- Lack of a universal data collection system where data can be extracted and retrieved through other industry standard communication protocols (e.g., Lonworks, Modbus, etc).
- Lack of a secure, scalable and industry standard oriented storage mechanism for both static and real time dynamic building operational data.
- Lack of a standard Application Programming Interface (APIs) that enable applications to programmatically extract data from the system, perform calculations outside of the middleware and finally write data back to the middleware. Examples of such applications are building performance simulation programs, FDD tools, visualization, controls and optimization tools.
- Lack of common computational services such as on-line parameter estimation and on-line model calibration that can be deployed as part of the middleware.

To address these gaps, it is recommended that the following activities should occur after this project:

- Extend a BACnet compatible data acquisition system to cover the other industry standard communication protocols.
- Develop a database structure that enables rapid mapping and use of both static building information and real time dynamic operational data during the design and operational phases of a building lifecycle. This structure should be tested in a variety of buildings with different types and sizes.
- Develop a services-based architecture to support the data exchange APIs and computational services.

### **Network Communication**

Significant challenges were encountered in the development and testing of the advanced building energy management system tool because of remote access problems. Network security constraints prevented the team from having remote access to the computers at Great Lakes. This

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<sup>19</sup> Building Control Virtual Test Bed <http://simulationresearch.lbl.gov/bcvtb/>

presented a significant challenge for coding and debugging. Team members could do efficient debugging only while visiting the site. This made it harder for the team to troubleshoot and fix complex and unforeseen issues with the code. It is recommended that remote access be granted for developers implementing similar systems at other sites. This access should be in compliance with DoD IT policy including Navy Public Service Network. Also, a secured and integrated DoD network should be established for building applications.

### **Performance Visualization User Interface**

The visualization interface has been refined and adapted based on feedback received from the facility team at the Great Lakes site. The UTRC team visited the Great Lakes site in September, 2011, February and May, 2011. The visualization frontend was demonstrated to the facility team. The facility team was satisfied with the functionality of the tool but had several suggestions regarding aspects of visualization. Most of the suggestions were refinements that would improve usability of the tool. New visualizations that allow a user to compare building energy performance between two time periods and across various outside air temperature ranges have been implemented. New features that implement carpet plots have also been included into the existing user interfaces. A user friendly and modular user interface (UI) was developed to facilitate navigation through a large database. Gaps are listed as follows:

- Lack of a UI that allows users to rapidly build their own visualization screens containing charts and 3D graphics.
- Lack of functionality for generating comprehensive reports that can be sent in real time to the facility team.
- Lack of a standard and common building operation interface that can be integrated with the BMS in all DoD buildings

To address these gaps, it is recommended that the following activities should occur after this project:

- Develop a flexible and extensible Energy Human Machine Interface (eHMI) that enables rapid development by common DoD facility users.
- Develop a standard mobile application for the aBEMS. This will make the recommendations provided by the aBEMS immediately visible and actionable.

### **Required Skills**

Using this advanced building energy management system currently requires the installer to have the following skills:

- **Create a ROM.** A library for building envelope and HVAC system reduced-order models was created. The Appendices E and G provide detailed descriptions of ROM for demonstration buildings used in the project. The BIM to BEM toolkit developed in this project help users to automatically generate ROM building envelope model.
- **Set up the data acquisition system.** A Building Data Acquisition System (BDAS) was created using an open source software environment. A detailed description of the steps required to use the BDAS is provided in Appendix I.
- **Set up FDD models.** Detailed instructions for setting up the necessary files and providing data for training the diagnostic models are described in the Training Documentation. The user will need to run a MATLAB script after validated data corresponding to nominal behavior is selected.

In summary, during the demonstration process at Naval Station Great Lakes, the maturity of the different technology elements have been assessed with gaps identified that will impact the successful deployment of a building energy performance monitoring and diagnostics system. After the completion of the Naval Station Great Lakes demonstration, it is recommended that the following list of activities should occur to ensure widespread technology deployment at the DoD.

- 1) Develop low cost and scalable building energy monitoring systems.
- 2) Implement a robust and scalable middleware for DoD buildings.
- 3) Deploy a secured DoD network for energy efficient buildings.
- 4) Integrate Energy Human Machine Interface (eHMI) applications for DoD building facility operations.

The rationale and details for these recommendations are provided in Appendix K: “Response to the ESTCP IPR action items”.

## 8.0 TECHNOLOGY TRANSFER

### 8.1 COMMERCIALIZATION AND IMPLEMENTATION

During the demonstration, the UTC stage-gated technology and product development processes have been applied to begin transitioning the technology into a commercial product. The Advanced Building Energy Management System (aBEMS) can be a part of a new BMS product or can be applied as an overlay on an existing BMS. To support a large-scale DoD deployment, UTRC has been engaging expertise from UTC businesses:

- Automated Logic Corporation (ALC) – The demonstrated technology elements including BMS integration (middleware), energy diagnostics, and HVAC operation sensitivity analysis can be integrated into the ALC WebCTRL BMS.
- NORESO provides energy services to DoD facilities worldwide.

### 8.2 TRAINING REQUIREMENTS AND RESOURCES

Technical/Educational Sessions: The results of the technology demonstrated in this project have been or will be presented in the following events.

#### Journal and Conference Papers

- 1) Dong, B., Z. O'Neill, D. Luo and T. Bailey. 2013. Development and Calibration of a Reduced-order Energy Performance Model for a Mixed-use Building, Accepted. *The 13th International Building Performance Simulation Association Conference and Exhibition*.
- 2) O'Neill, Z. and T. Bailey, B. Dong, D. Lou and M. Shashanka. 2012. Advanced Building Energy Management Systems. Invited paper, submitted to *Annals of the New York Academy of Sciences*.
- 3) Li, Z., B. Dong, Z. O'Neill and G. Augenbroe. 2012. A Streamlined Workflow Process and Related Infrastructure for Building Fault Detection and Diagnostics. Submitted to *Automation in Construction*.
- 4) Dong, B., Z. O'Neill, D. Luo, S. Ahuja and T. Bailey. 2012. An Integrated Infrastructure for Real-Time Building Energy Modeling and FDD. *The Fifth National Conference of IBPSA-USA: SimBuild2012*. Madison, Wisconsin. August 1–3, 2012.
- 5) Li, Z., B. Dong and Z. O'Neill. 2011. Database Supported BACNet Data Acquisition System for Building Energy Diagnostics. *The 11th International Conference for Enhanced Building Operations*. New York City, NY. October 18–20, 2011.

#### Presentations

- 6) Scalable Advanced Building Energy Management Systems. SERDP/ESTCP Symposium. Washington, D.C. November 29 –December 1. 2011.
- 7) Advanced Building Energy Management Systems Demonstration. EPA Green Building Research Symposium. Philadelphia, PA, July 17, 2012.
- 8) A Reduced-order Energy Performance Modeling Approach for Buildings. Invited presentation. SIAM CS&E 2013. Boston, MA, February 25 to March 1, 2013.

End User Training: The team has provided user training to the facility team at Great Lakes. Three on-site demonstration and training sessions with Great Lakes facility team were held in the demonstration building on September 12, 2011, January 12, 2012 and May 16, 2012. Figure 8.1 shows the training session on May 16<sup>th</sup>, 2012.



Figure 8.1 Training session in Great Lakes on May 16, 2012

A training documentation was completed and will be available upon request from ESTCP program office. The demonstrated advanced building energy management system was introduced in the EPA Green Building Research Symposium on July 17<sup>th</sup>, 2012 in Philadelphia, PA. The seminar was well received and the team was invited to submit a Journal paper to a special issue of Annals of the New York Academy of Sciences that discusses the implications of a data-driven built environment.

In the future, the team will attend specific conferences such as SERDP/ESTCP Symposium and webinars such as FEMP's First Thursday's program to reach a broad government audience.

### **8.3 DESIGN COMMUNITY IMPACTS**

This project has identified a key remaining barrier for broader DoD deployment which is the initial cost related to energy monitoring systems necessary to enable advanced building energy management system. Currently, the DoD does not have a design guideline to determine the minimum set of sensors needed by energy monitoring systems (including electrical and thermal) for both new building design and existing building retrofit scenarios. A *DoD Building Energy Monitoring Design Guideline* to determine the minimum set of sensors is needed. Existing reports [23] for building sub-metering systems should be incorporated and adapted. This design guideline should include a check list of sensors and decision flow charts that will help facilitate the deployment of advanced building energy management system across DoD facilities.

Recommendations that emerged from this demonstration that relate to building energy monitoring system, middleware, and a secured DoD network for energy efficient buildings should be integrated within DoD Energy Manager's Handbook.

The DoD should begin to publish guidelines and standards in the following areas to facilitate the deployment of advanced building energy management systems across DoD buildings and facilities:

- A design guideline to determine the minimum set of sensors/meters required to deploy a comprehensive energy monitoring system for both new construction and retrofit of existing buildings. This guideline should include a check list of sensors/meters and decision flow charts for different HVAC systems.
- A guideline to establish a secured and integrated DoD network for building applications.
- A standard to share building energy usage data via a secured network using native communication protocols such as BACnet and Lonworks etc.
- A standardized process to automatically collect building information from available references and transfer them to building energy applications such as building energy models.

## **APPENDICES**

## **APPENDIX A: PERFORMANCE ASSESSMENT METHODOLOGIES**

The performance of the Advanced Building Energy Management System (aBEMS) has been assessed against the performance objectives listed in Table 5.1 in Section 5.0. Details about how these objectives were assessed are presented in the following subsections.

### **A.1 HVAC EQUIPMENT REDUCED-ORDER MODEL PERFORMANCE ASSESSMENT**

Details about HVAC equipment reduced-order model (e.g., equations, inputs and output etc.) are included in Appendix E. Models have been calibrated and validated except for the equipment without quality measured data (e.g., heat coils and absorption chiller) or with inconsistent operation patterns (e.g., economizers). Model parameters were first calibrated with one set of data that covered an appropriate range of operation (e.g., data of fan speed and power from May) and then applied to other sets of data (e.g., data from June/July). Deviation of energy consumption for each of the chillers, fans and pumps was within +/-10% based on the data used for validation. The absorption chiller model for Buildings 7113/7114 could be improved if more reliable measured data was available for heat input in normal operation. At the time when the test data was collected, one of the two absorption chillers stopped working while the other one that was working has inappropriate operating status and was under repair.

#### **Air Cooled Electric Chiller**

For the air-cooled electric chillers in Building 7230 values of model parameters were determined from catalog and some measured data. The parameters were then used to tune the model with data in July 2010 and validated with data in May, June and August 2010, as shown in Figures A.1 and A.2. Difference between measured data and model prediction of electric energy consumption of chillers in Building 7230 was within 1%. Magnitude of errors was mainly affected by the load level, with larger errors under low load conditions, e.g., 24.7% with mild ambient weather in May in this case, and smaller errors under higher load conditions, e.g., 6.9% in June and around 3.5% in July and August. Electric energy consumption under low load conditions was much smaller than that at higher load conditions, impact of the deviation from measured data under low load conditions became negligible compared to the total energy consumption. For example, in this study, electric energy consumption of the chillers in May accounted for only 2.3% of the total during May-August. In the scatter plot shown in Figure A.3, the size of each circle represents monthly load as a percentage of the total, while the color represents the model prediction error in percentage.

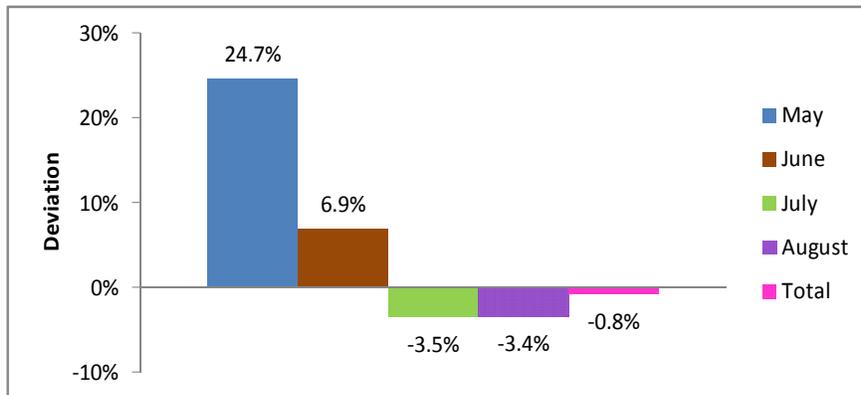


Figure A.1 Error of Model Prediction of Electric Energy for Chiller 1 in Building 7230

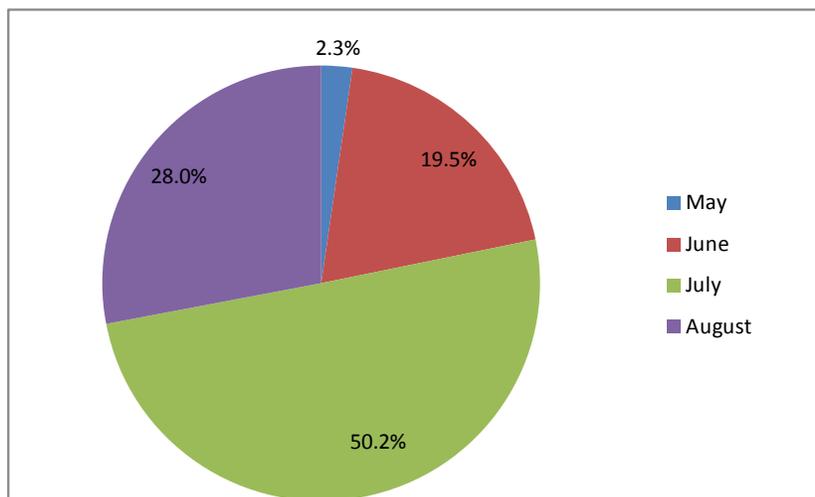


Figure A.2 Monthly Distribution of Electric Energy Consumption of Chiller 1 in Building 7230

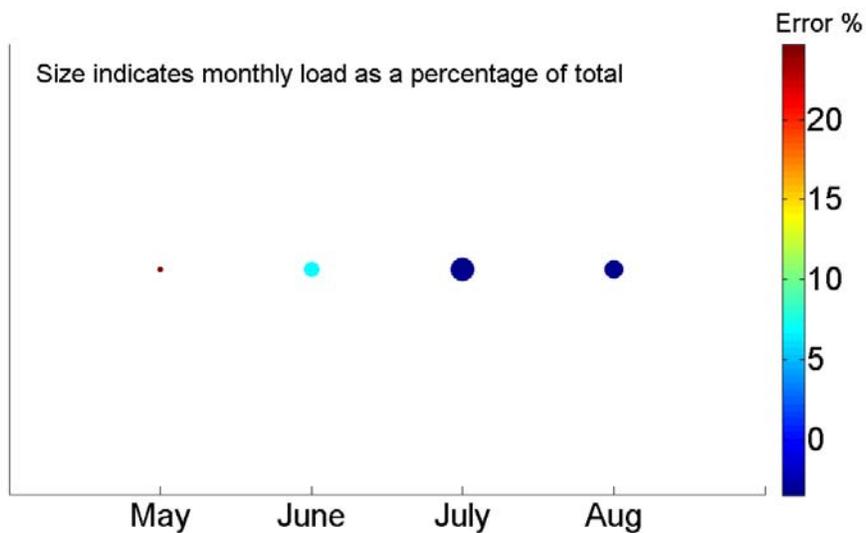


Figure A.3 Scatter Plot of Model Prediction Error of Electric Energy for Chiller 1 in Building 7230

### Absorption Chiller

For the steam driven absorption chillers in Building 7113/7114, values of model parameters were determined from a chiller product catalog and some measured data. The parameters were then used to tune and validate the model with data in June through August 2011. Difference between measured data and model prediction of steam consumption of chiller in Building 7113/7114 was within 10%. Larger deviations occurred under low load conditions.

Although deviation of predicted accumulated energy consumption from measurement was reduced to within 10%, the error of heat input rate data was relatively large at a given time point. Data quality was not appropriate due to the abnormal operating status of the chillers as reported later by the facility staff during the period when data was collected. Chiller 1 was not working and chiller 2 was not able to maintain the chilled water setpoint. With data collected during the cooling season during June 1 – August 4, 2011, data trends did not reflect the physics in a consistent manner for reliable prediction of heat input, as shown in Figure A.4. Given the quality of data used for the current model, it is recommended that the model coefficients should be recreated when data with high quality is available.

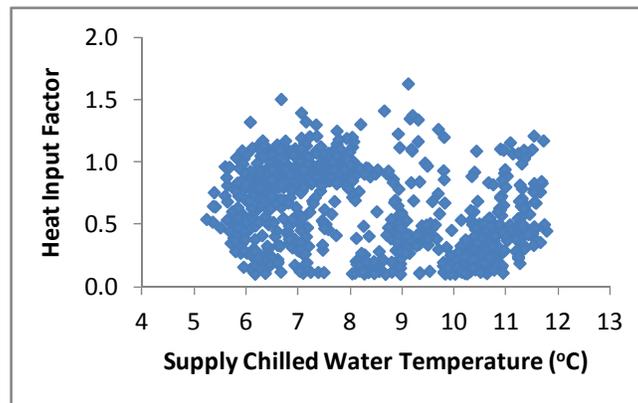
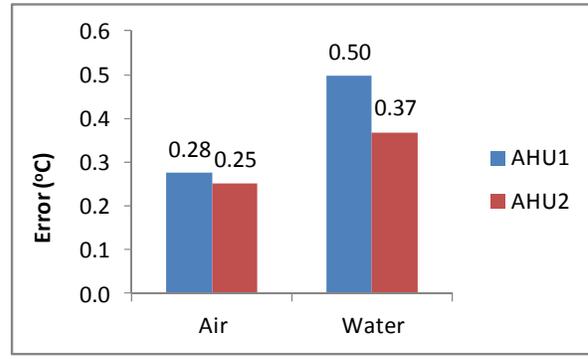
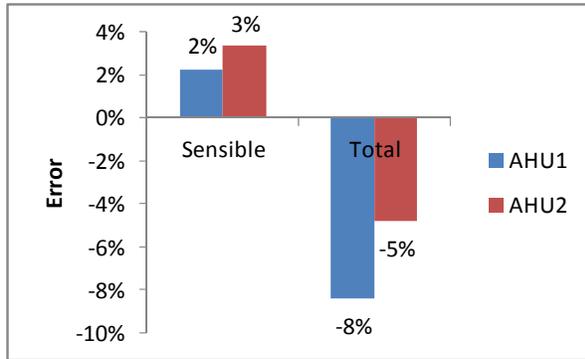


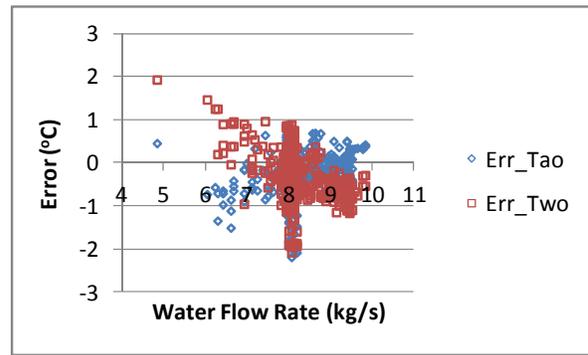
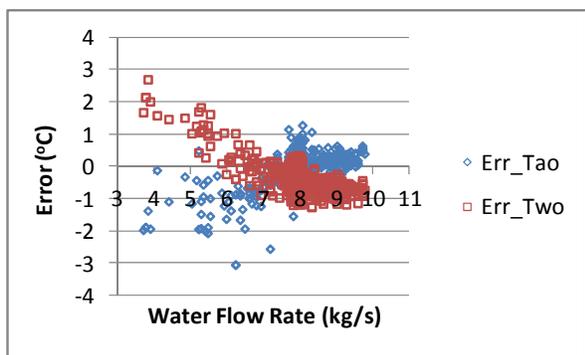
Figure A.4 Heat Input Factor (Heat Input Divided by Design Value) vs. Supply Chilled Water Temperature of Chiller 2 in Building 7114

### Cooling Coil

For the cooling coils in the air handling units 1 and 2 in Building 7230, UA values were first calculated with data from the design schedule. With the design UA values as a reference, test data in June-July 2011 were used to calibrate the UA values to achieve minimum deviations of leaving air and water temperatures between model and data. The calibrated UA values were then used to validate the model with data in August-September 2011. As shown in Figure A.5, difference in capacity on water side and sensible capacity on air side between model and data was less than 10%. The average difference in air and water leaving temperatures was less than 0.5°C. However, large temperature deviations occurred at low water flow rates, as shown in Figure A.6.



Capacity Error Leaving Air and Water Temperature Error  
 Figure A.5 Average Errors of the Cooling Coil Model Prediction of AHUs in Building 7230



AHU1 AHU2  
 Figure A.6 Errors of Air and Water Temperatures Leaving Cooling Coil in Building 7230

### Fan

Models have been created for the VFD fans and pumps in Building 7230 and Building 7113/7114. For Building 7230, data of one month from May-August 2010 were used to generate the coefficients and data in the other two months were used for validation. For Building 7113/7114, data from June-July were used to generate coefficients and data from August-September were used for validation.

As shown in Figure A.7, for Building 7230, fan power input was calculated as a function of air flow rate. Error of accumulated electric energy consumption of fan/pump was less than 10% (power as a function of air flow rate) except for return fan 1 (RF1), which account for 9% of the total as shown in Figure A.8. Total electric energy consumption was negligible. For Building 7113/7114, fan power input was calculated as a function of fan speed control signal. Error of accumulated energy consumption was less than 1% and error of the predicted total electric consumption is negligible.

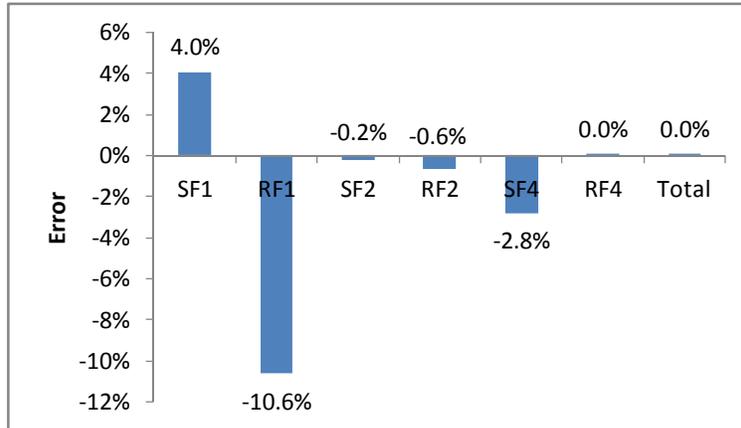


Figure A.7 Error of Model Prediction of Electric Energy of VFD Fans in Building 7230

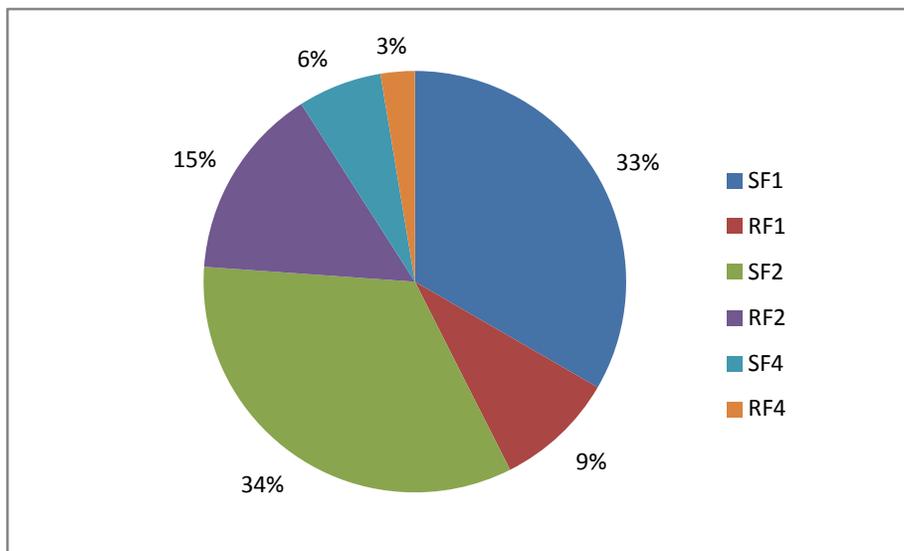


Figure A.8 Distribution of Electric Energy Consumption of VFD Fans in the Drill Hall

### VAV

For Building 7230, UA values of the reheat coil were derived from the design schedule. The minimum air flow fraction was refined with actual field data. However, the minimum air flow control was not maintained in heating mode in some of the VAVs as they were designed. For the ones that were maintained at a relatively constant minimum air flow rate, deviations of leaving air temperature after reheat were less than 1°C, with an average of 0.14 °C, as shown in Figure A.9. In cooling mode, the relative errors of air flow rate were within 10%, with an average of 3%, as shown in Figure A.10.

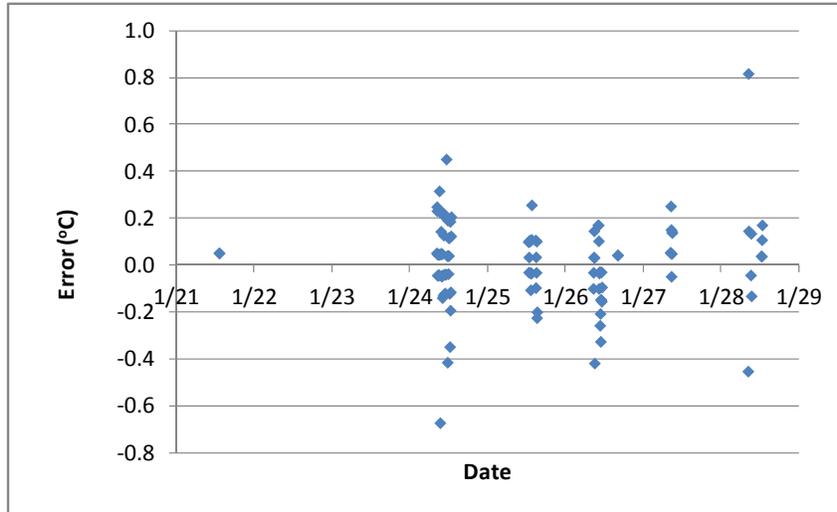


Figure A.9 Error of Model Prediction of Air Temperature Leaving VAV1 of Building 7230 in Heating Mode

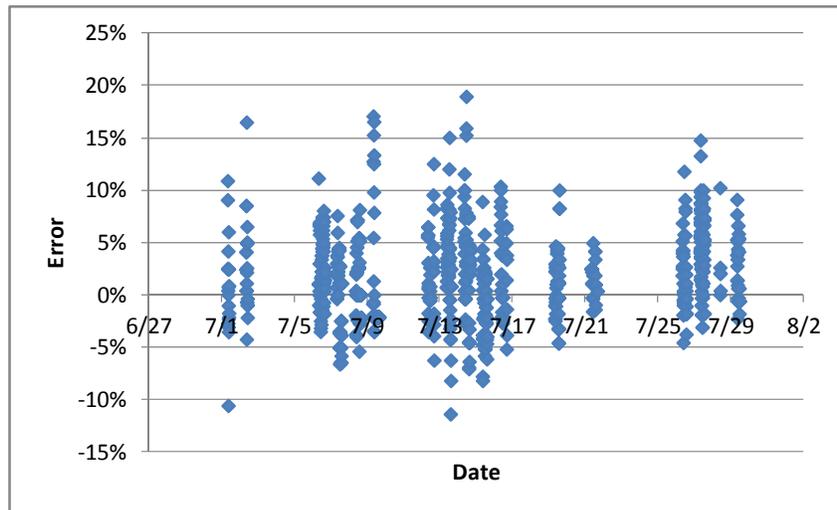


Figure A.10 Error of Model Prediction of Air Flow Rate of VAV1 of Building 7230 in Cooling Mode

For Building 7113/7114, data was not sufficient for model validation and therefore models have been only reviewed in trends. Wide bands in data of air flow rate vs. damper position were observed in all the selected VAV units.

## A.2 INTEGRATED SYSTEM MODEL PERFORMANCE ASSESSMENT

The system model performance validation consists of four parts:

- Comparison of the building load predictions from building envelope ROM with the EnergyPlus model. In this case, a comparison of the ROM with a calibrated EnergyPlus model was conducted for Building 7230. The results showed the differences were less than 3% for the cooling season and 11% for the heating season.

- Comparison of the building load predictions from the building envelope ROM with measured data. In this case, the loads predicted from the ROM and those calculated from measured data for Building 7230 and Building 7114 were compared. For Building 7230, the load predictions were within the  $\pm 5\%$  error band for the cooling season and the  $\pm 17\%$  for the heating season. For Building 7114, the model predictions were within the  $\pm 11\%$  error band for all the AHUs during the cooling season.
- Comparison of the building load predictions from the integrated ROM including the HVAC ROM with measured data. In this case, a comparison between the integrated ROM and measurements was conducted. For Building 7230, a comparison of the simulated and measured monthly hot water consumption showed the difference was less than 5% for January, 2011. For Building 7113/7114, 75% to 85% of the data was within  $\pm 15\%$  error band in each time step (i.e., 5 minutes) during both cooling and heating typical days.
- Comparison of lighting and plug loads between the model predictions and measurements. In this case, a comparison of monthly total predictions from June to December, 2011 for both lighting and plugs with measured data was conducted. The result showed differences were from -0.22% to 2.91% for monthly total lighting and plug loads.

Overall, the performance objective for the ROM was achieved where the prediction accuracy was within  $\pm 15\%$  for the overall building load predictions.

### **Comparison of Results from EnergyPlus**

A comparison of load predictions between the ROM and the EnergyPlus model was conducted for Building 7230 where there was a calibrated EnergyPlus model [16].

As a first step, the predictions of the thermal network model were compared to that of a higher-fidelity EnergyPlus model of the building that was developed in a companion project. Thus, the uncertainties could be minimized, since the thermal parameters (resistance  $R$ , Capacitance  $C$ ) and the internal heat gains used were exactly the same as that in EnergyPlus. Further, the same weather data was used in both the models; in particular, TMY3 data for Waukegan, IL was used, which is the nearest airport to this building. The supply air conditions were also obtained from EnergyPlus: Please note that the EnergyPlus model is a “steady-state” model that achieves required set-points at all times (within the constraints of the HVAC system). On the other hand, the thermal network model was an open-loop model, with no feedback to the controller. This results in a validation of just the building envelope model before integrating it with the HVAC system models.

The results of the thermal network model were compared in Figure A.11. The figure compared the monthly integrated loads predicted by the two models; thus, for each zone, the total cooling or heating loads was computed for a given month, and a percentage error was computed, with respect to the EnergyPlus predictions. In the scatter plot shown in the figure, the size of each circle represents the load in the zone, while the color represents the percentage error. The months are along the  $y$ -axis, with January=1 and so on. The zones 1-12 represent the first floor (office area), 14-19 the second floor (class-room), while zones 24-35 represent the drill-deck. The zones with largest loads are the classroom and the drill-deck. The two models compare very well, to within 5% accuracy for the summer months (May-September). But the main source of

inaccuracy is in the winter months. The reasons for such difference is that supply air temperature (24°C) was set very close to the zonal set-points (21°C) during the winter months in the EnergyPlus model. Depending on the disturbances (e.g., outside conditions and building usage etc. ), the load often fluctuated between cooling and heating; due to that, the two models often predicted opposite signs of loads, thus resulting in large percentage errors. The results were expected to be closer if the difference in the supply air temperature and zonal set-points are sufficiently large. The actual supply air temperatures in the building were much larger than those used in the EnergyPlus model, thus rendering it inaccurate for this operation. The annual and peak loads of the entire building are tabulated in Table A.1Table A.1; these show that the comparison is within 3% for the cooling operation and approximately 11% for the heating operation.

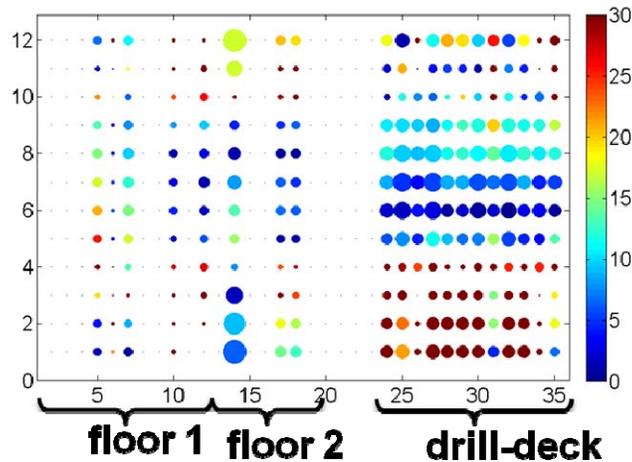


Figure A.11 Scatter Plot for Load Prediction Errors by Thermal Network Model (Compared with EnergyPlus)

Table A.1 Annual and Peak Load Comparison Between EnergyPlus and Thermal Network Models for Drill Hall

Loads (building level)	EnergyPlus	RC Model	Error*
Annual cooling (MW-hr)	169.3	174.7	3.2%
Peak cooling (kW)	140.6	144.4	2.7%
Annual heating (MW-hr)	96.1	106.7	10.9%
Peak heating (kW)	174.2	162.6	6.7%

\* The error was computed relative to the predictions of the EnergyPlus model

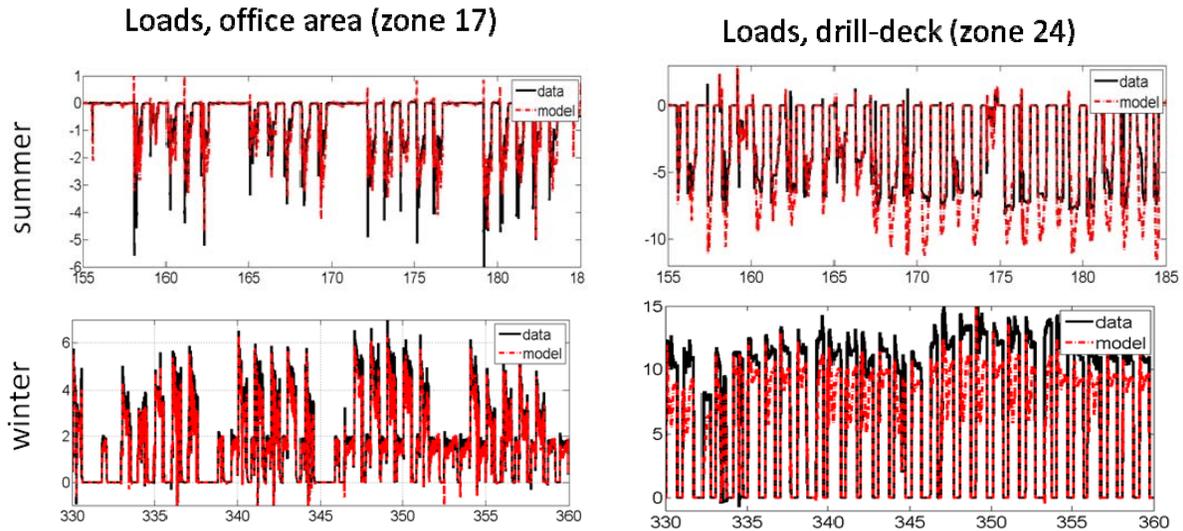
### Building Load Comparison

During this step, the loads predicted from the reduced-order model were compared with the ones calculated from measurements. Those tests were conducted for two buildings:

#### Case 1: Building 7230(Drill Hall)

The results of the calibrated model are shown in Figure A. 12, A.13, and Table A.2. Figure A.12 shows loads predicted by the thermal network model (black) with data (red) for two periods of one month each. The left Y axis in Figure A.13 shows the percentage errors, the X axis shows the number of zones. The size of the bubbles shows the amount of energy consumed, the bigger

the bubble, the larger the energy consumption. The comparisons are shown for the period of June to December 2011. The predictions were again within 5% of measurements for the cooling operation, but the error is higher for the heating operation. Note that, in the actual operation, the loads are dominant in the drill-deck, while the classroom has much smaller load. The discrepancies were justified in the winter operation as follows: the lumped well-mixed air model for the drill-deck, which is a large open space with a floor-to-ceiling height ranging from 8 meters to 14m, is inadequate.



The plot shows data for zones 17 (office area, left) and 24 (drill-deck, right) for two periods from May 4 – June 5 (top) and Nov 25 – Dec 25 (bottom).

Figure A.12 Load Comparisons Between Data and Thermal Network Model.

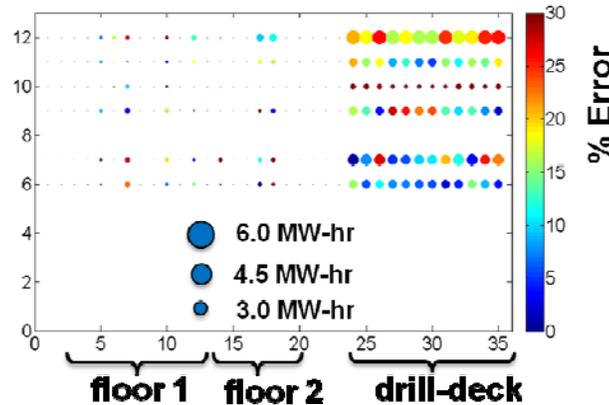


Figure A.13 Scatter Plot for Load Prediction Errors by Thermal Network Model (Compared with Data)

Table A.2 Annual and Peak Load Comparisons between Data and Thermal Network Models for the Building 7230

Loads (building level)	Data	RC Model	Error
Annual cooling (MW-hr)	101.9	106.4	4.4%

Peak cooling (kW)	182.7	153.1	16.2 %
Annual heating (MW-hr)	92.1	75.6	17.9 %
Peak heating (kW)	235.0	180.9	23.0 %

*Case 2: Building 7114*

The Building 7114 envelope model was calibrated and the results are illustrated in Figure A.14, which show scatter plots similar to the ones shown in the previous case study. The axes are similar to that in Figure A.13. The data was available for months of July and August only (cooling operation), as indicated by the month numbers on the y-axis. The first figure shows the compartment zones, and the largest circles (recall, the larger the diameter of the circle, the larger is the load) indeed represent the large sleeping areas. For most of the zones, the error ranges from 5-10% (indicated by the color); however, there are some zones with much larger error up to 30%. Figure A.15 shows a similar plot for the classroom zones served by AHU3 for July and August in 2011. The comparison at the AHU level is summarized in Table A.3, which shows that indeed, the model predictions are within 10-11% of the measurements for all the AHUs.

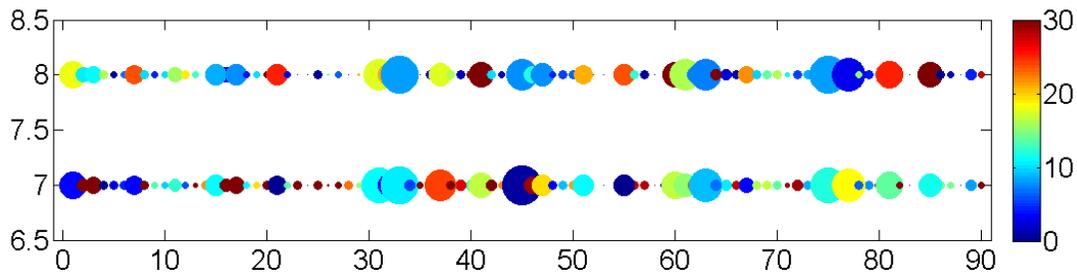


Figure A.14 Scatter Plot for Load Comparisons (Zones Served by AHU 1/2 in Building 7114).

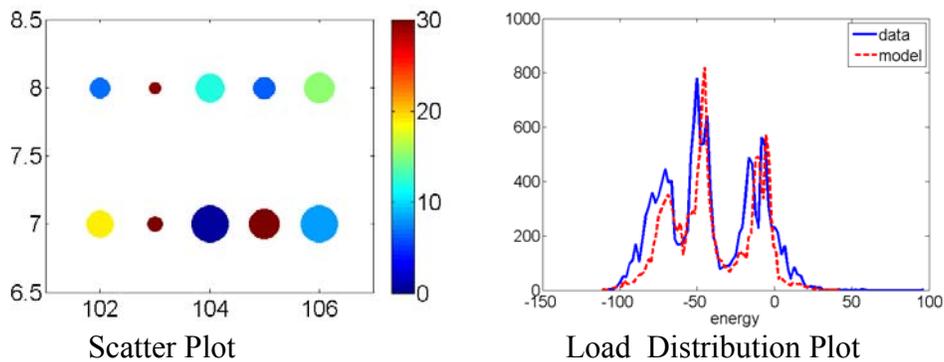


Figure A.15 Load Comparisons Results for Classroom Zones Served by AHU3

Table A.3 Comparisons of Building 7114 Cooling Load at the AHU Level between Data and Thermal Network Models for July and August 2011

AHU	Loads, data	Loads, model	Error
1	112.1	104.6	11.1%
2	103.8	98.4	11.7%
3	54.4	51.8	9.7%

## HVAC Load Comparison with Integrated Models

### Case 1: Building 7230

Similar to the previous case, a comparison between integrated model and EnergyPlus model was conducted as the first step for Building 7230. The results are shown in Figure A.16 and A.17. Figure A.16 shows the results from Aug. 1<sup>st</sup> to Aug. 5<sup>th</sup>, 2010, where 80% of the data is within  $\pm 20\%$  error band. The large errors appear during the system start-up time period. This is due to the nature of steady-state HVAC model, which cannot simulate the dynamics. The similar pattern observed for heating season comparison which is from Nov. 27<sup>th</sup> to Dec. 1<sup>st</sup>, 2010. During this period, 75% of the data is within  $\pm 20\%$  error band.

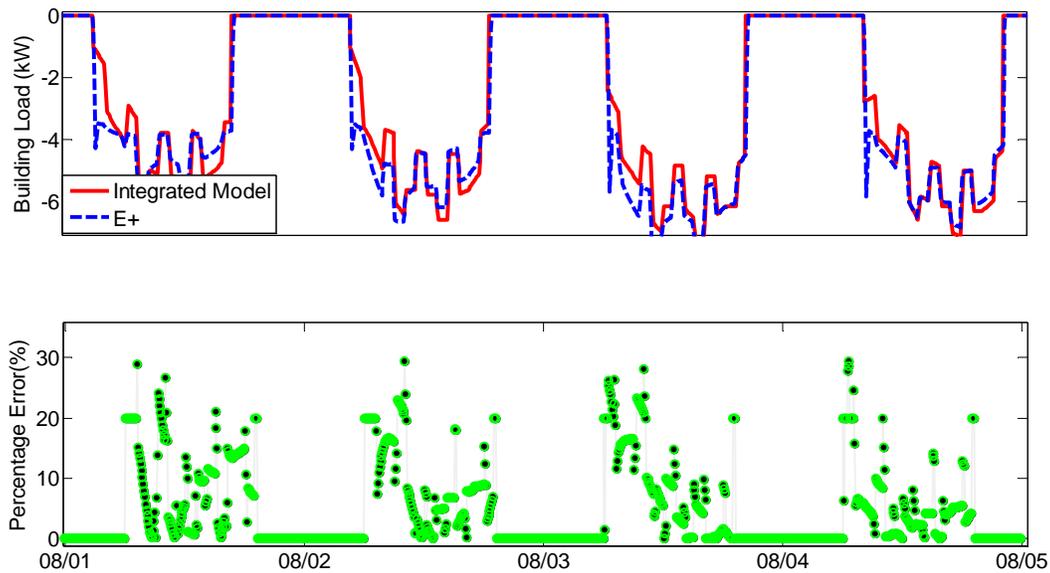


Figure A.16 Comparisons Between ROM and EnergyPlus Total Building Load for Cooling Season

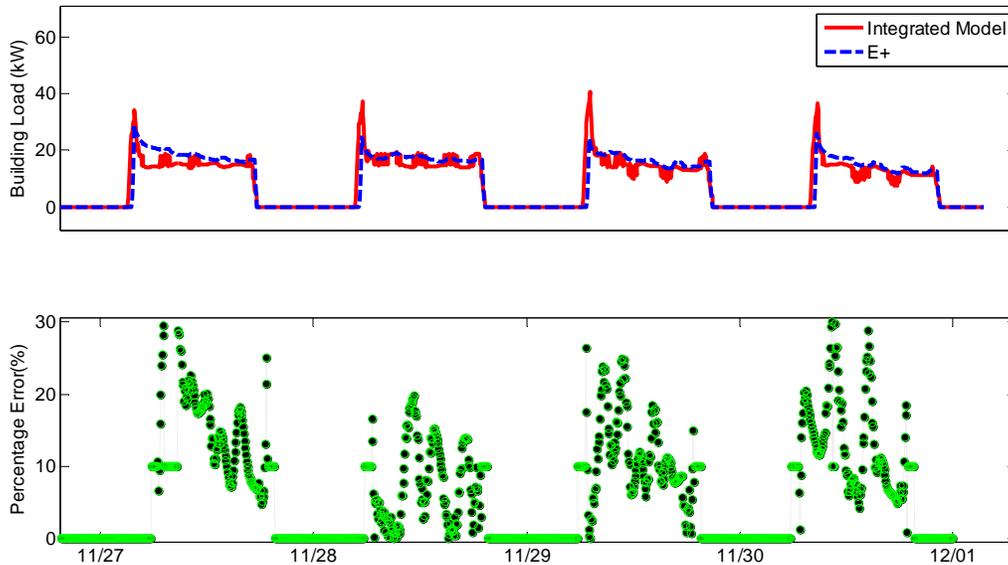


Figure A.17 Comparisons Between ROM and EnergyPlus Total Building Load for Heating Season

Figure A.18 shows a comparison of hot water energy consumption between ROM and measured data in January 2011. The difference between total monthly hot water energy consumption predicted by ROM and the measurement is within  $\pm 5\%$  error band. Again it is observed that there are some spikes due to the transient effects from the measured data where the low load conditions happened.

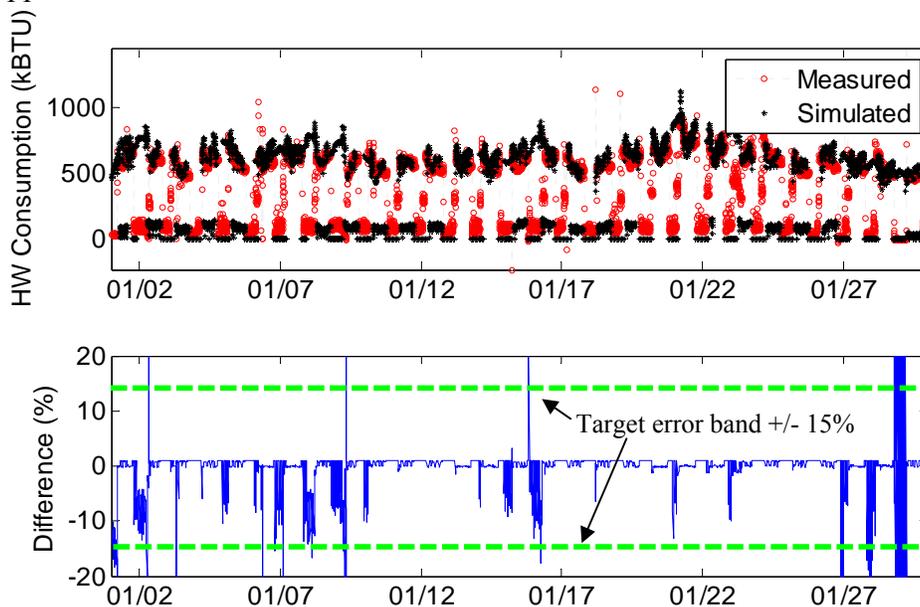


Figure A.18 Comparisons of Hot Water Energy Consumption Between ROM and Measurements in January, 2011

Case 2: Building 7113/7114

For Building 7113 and 7114, a whole year simulation was conducted and the results are shown in Figure A.19. The left axis shows the total thermal energy consumption and the right axis shows the percentage of simulation data points versus measured data points. Due to a BMS server issue and power outage in Building 7113/7114, the measured data points were not collected continuously for the whole year. However, the weather data, used as thermal boundary conditions to drive the simulation, were collected independent from Building 7230 and are complete for the whole year. In Figure A.19, the right axis shows the percentage of available measured data points versus simulation data points. If the result is 100%, it means simulation result has the same number of data points of measured ones. Figure A.19 shows only a few months have the complete measured data points in 2011. In addition, the control logics for the simulation model are from the as-built control logic diagram provided by the BMS vendor. As shown in Figure A.19, there are some energy consumption differences for June and July, which are 44% and 66% respectively. This is due to faulty control logics in the building energy management system. Based on these facts, validating the model on a yearly or monthly basis becomes difficult. Hence, the model validations for Building 7113 /7114 were conducted for selected days with normal operation.

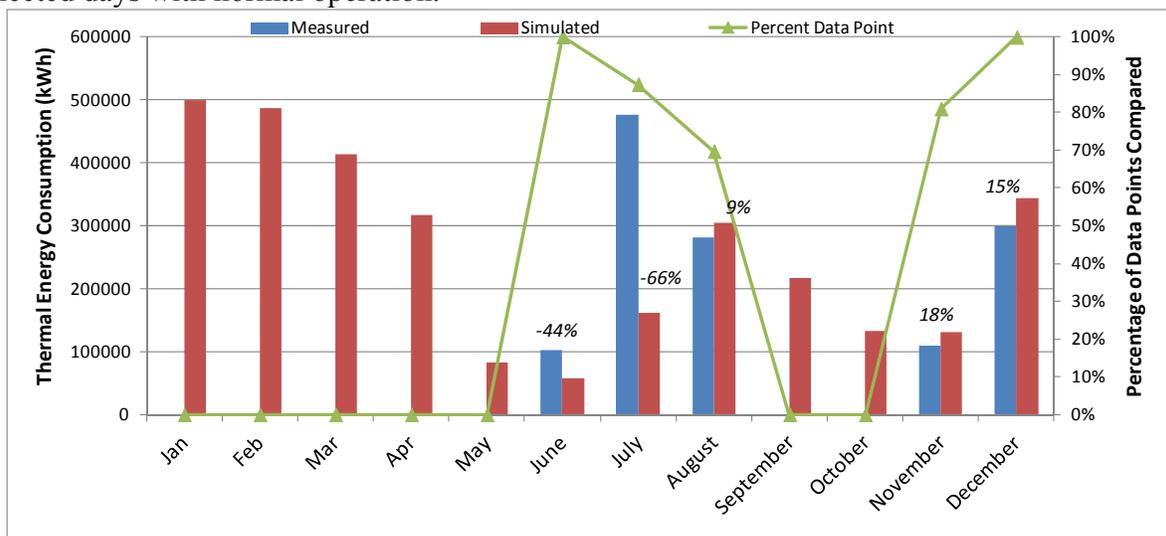


Figure A.19 Annual Energy Simulation Results for Building 7114 in 2011

Based on the results from annual model simulation results, the integrated model validation was conducted based on the valid measured data. During the cooling season, the zone daily occupied set-point is 70 °F and night set-back is 78 °F. During the heating season, the zone daily occupied set-point is 72 °F and night set-back is 65 °F. Those set-points are derived from BMS measured data.

There are six periods for model validations as follows:

#### 1) Building 7114 cooling period

The cooling model validation for Building 7114 was conducted from July 6<sup>th</sup> to July 9<sup>th</sup>, 2011 as shown in Figure A.20. About 85% of the data is within the ±15% error band in each time step (5 minutes). During the day time, the predicted loads from the model are very close to the ±10% error band. However, the model did not behave well during the middle of night due to the low load conditions.

## 2) Building 7114 heating period

The heating model validation for Building 7114 was conducted from Dec 8<sup>th</sup> to Dec 10<sup>th</sup>, 2011 as shown in Figure A.21 below. About 75% of the data is within the  $\pm 15\%$  error band in each time step (5 minutes). The main reason that the model prediction in the heating season is not as good as that in the cooling season is due to the fluctuation of water flow rate measurements.

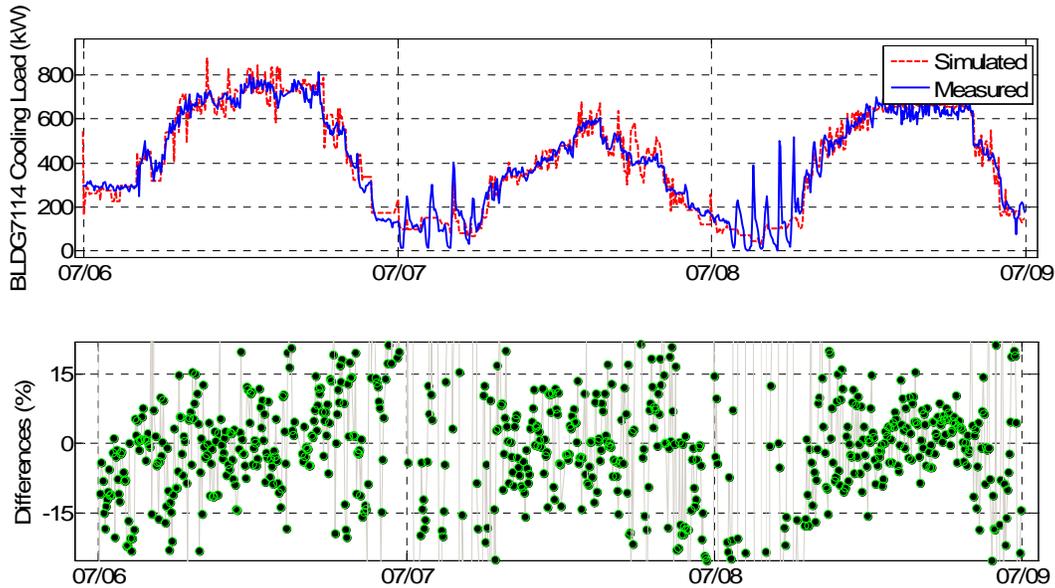


Figure A.20 Building 7114 Cooling Season Integrated Model Validation from 07/06/2011 to 07/10/2011

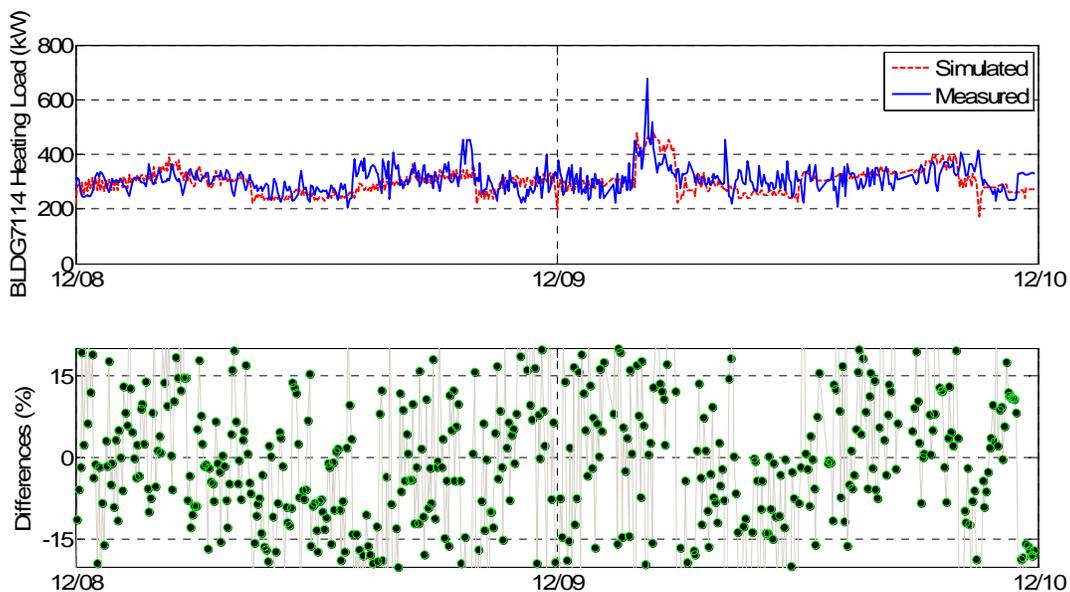


Figure A.21 Building 7114 Heating Season Integrated Model Validation from 12/08/2011 to

12/10/2011

### 3) Building 7113 cooling period

The cooling model validation for Building 7113 was conducted from July 7<sup>th</sup> to July 11<sup>th</sup>, 2011 as shown in Figure A.22 below. 86% of the data is within the  $\pm 15\%$  error band in each time step (5 minutes). The simulation result during the early morning has the same behavior as in Building 7114 where the actual measured data fluctuates more than the simulated results. This is due to the low load conditions at that time. Most of the results during the day time are within the  $\pm 10\%$  error band.

### 4) Building 7113 heating period

The heating model validation for Building 7113 was conducted from Dec 8<sup>th</sup> to Dec 10<sup>th</sup>, 2011 as shown in Figure A.23 below. 82% of the data is within  $\pm 15\%$  the error band in each time step (5 minutes).

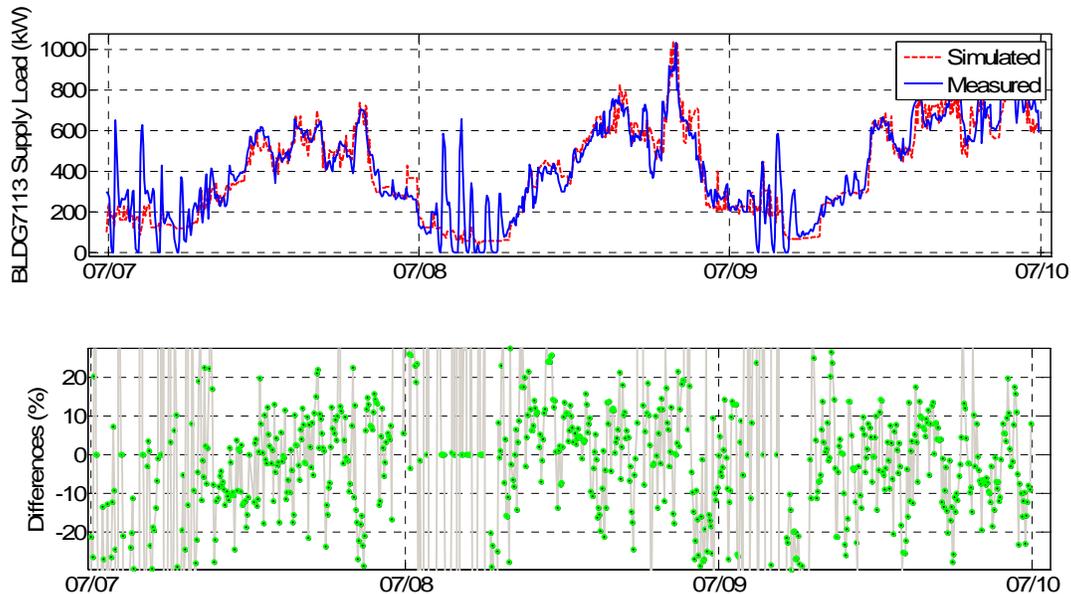


Figure A.22 Building 7113 Cooling Season Integrated Model Validation from 07/07/2011 to 07/10/2011

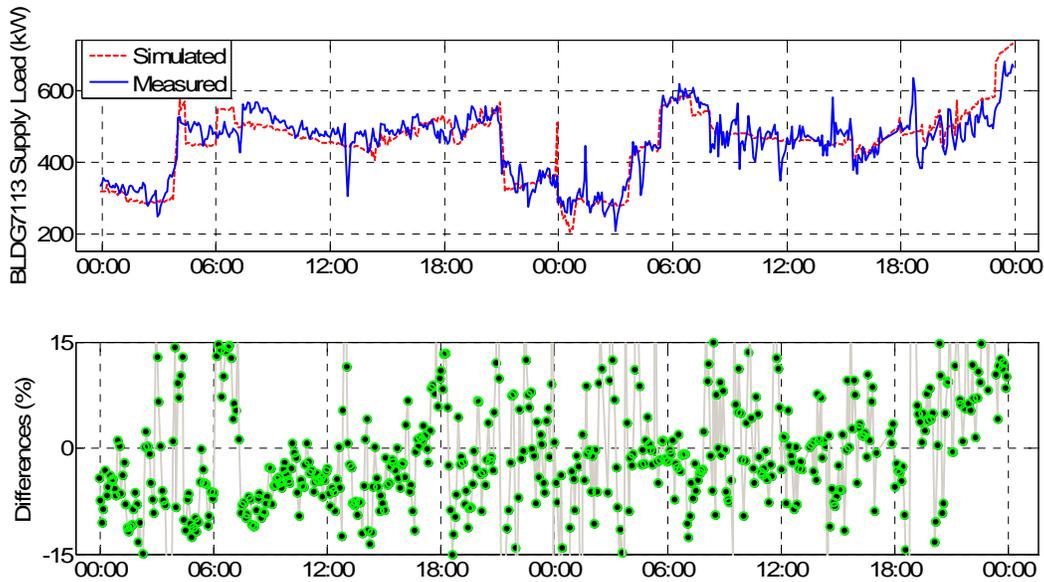


Figure A.23 Building 7113 Heating Season Integrated Model Validation from 12/08/2011 to 12/10/2011

#### 5) Campus building cooling period

Since Building 7113 and Building 7114 share the same chiller plant and cooling towers, a campus model was developed to simulate the energy performance of both two buildings. The cooling model validation for the campus was conducted from July 6<sup>th</sup> to July 10<sup>th</sup>, 2011 as shown in Figure A.24 below. About 82% of the data is within the  $\pm 15\%$  error band in each time step (5 minutes).

#### 6) Campus building heating period

The heating model validation for the campus was conducted from Dec 8<sup>th</sup> to Dec 10<sup>th</sup>, 2011 as shown in Figure A.25 below. About 80% of the data is within the  $\pm 15\%$  error band in each time step (5 minutes).

In summary, the total building load comparisons show that the differences between measurements and predicted building loads from the ROMs at each time step are within the  $\pm 15\%$  error band. This result gives us confidences on the model performance for those validated days, which are used for the HAVC operation sensitivity analysis. In addition, when low load conditions appear, the differences between simulated and measured tend to increase.

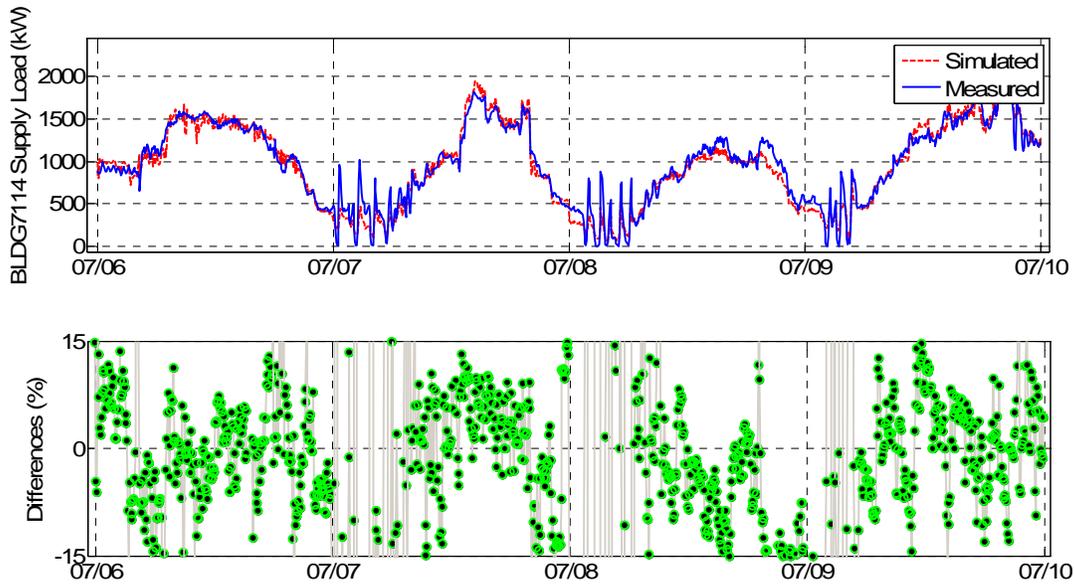


Figure A.24 Campus Cooling Season Integrated Model Validation from 07/06/2011 to 07/11/2011

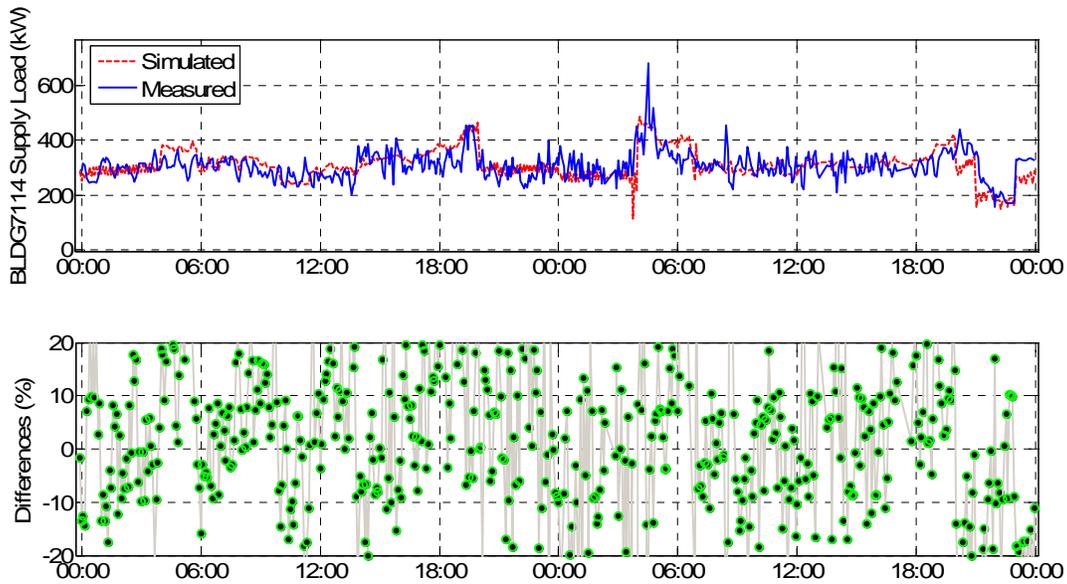


Figure A. 25 Campus Heating Season Integrated Model Validation from 12/08/2011 to 12/10/2011

### Comparison of Lighting and Plug Loads Between Model and Measurements

The comparison of lighting and plug loads between model predictions and measurements only occurs for Building 7114, as an example to show the model accuracy. Both loads were derived from measurement patterns and adjusted slightly for each month accordingly.

### Lighting load

For the lighting load, electric sub-meters were installed for emergence, compartments, classrooms and mechanical rooms. Since most of the occupant's activities happen in the compartments and classrooms area, the comparison is conducted for those two areas. Figure A.24 shows an example of the usage pattern of the compartment lighting from Aug.6<sup>th</sup> to Aug. 9<sup>th</sup>. 2011. The red line shows the measured lighting load, while the blue line shows the estimated pattern. They are very close to each other, although with some fluctuations during the afternoon time. If such estimation was applied on all other months, Figure A.27 shows the totally monthly loads comparisons from June to December, 2011, with accuracies on the right vertical axis. The worst case is the December with a difference of 1.78%, while the best case is the July with a difference of -0.22%.

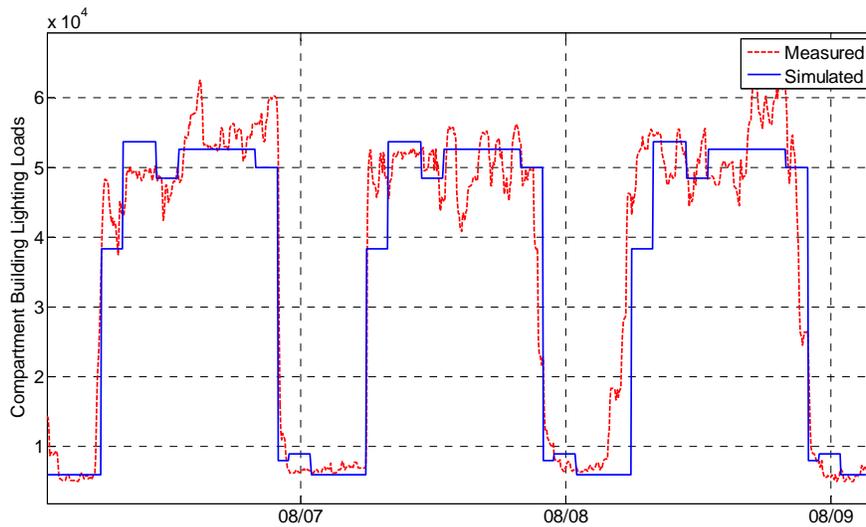


Figure A. 26 Comparisons between Measured and Estimated Lighting Loads in Building 7114 from 08/06/2011 to 08/09/2011

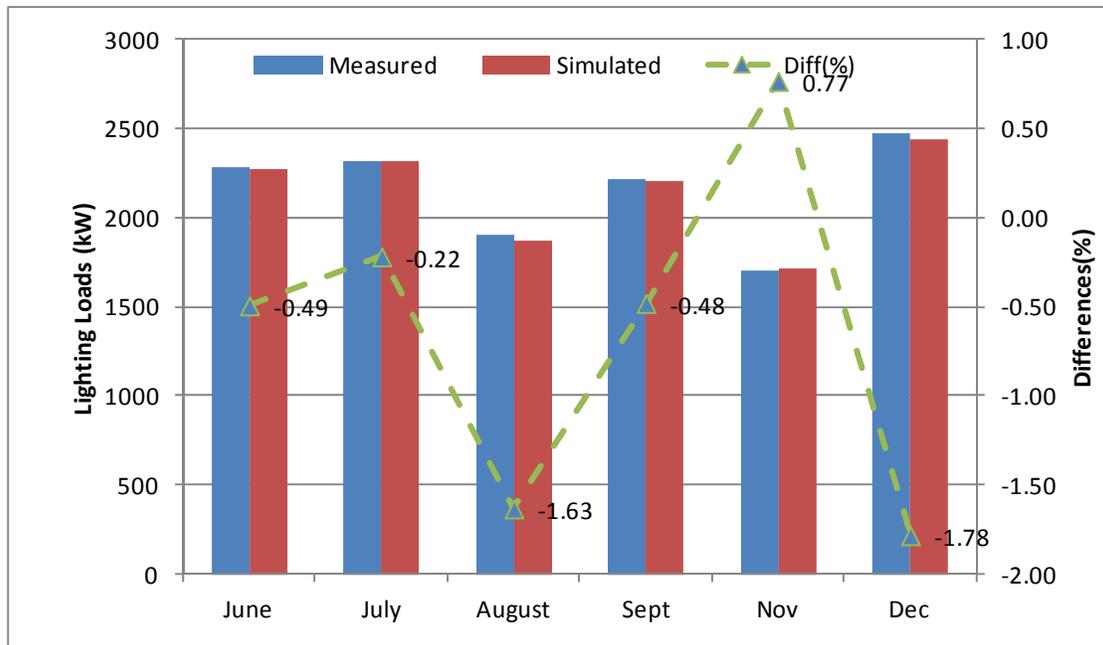


Figure A. 27 Comparisons between Measured and Estimated Lighting loads of Compartments and Classroom Areas in Building 7114 from June to December, 2011.

### *Plug load*

There is only one total building sub-meter for the plug loads, which makes the estimation difficult. The estimation follows the three steps: 1) Plug loads after mid-night are mostly from computers in the two classrooms; 2) Before dinner time (around 5 pm), the plug loads are mainly from compartments and classrooms; 3) During dinner time, the plug loads are from compartments, classrooms and kitchen/dining areas. Based on these heuristic rules, the comparison is shown in Figures A.28 and A.29. Figure A.28 shows the measured plug loads have spikes in the late afternoon but not for all days. Figure A.29 shows the total building plug load comparison from June to December, 2011. The best case is the December with a difference of -0.1%, while the worst case is the July with a difference of 2.91%. This could be due to a lower building occupancy in December and a relatively higher building occupancy in July. With the high occupancy, there are more uncertainties in the plug load estimation.

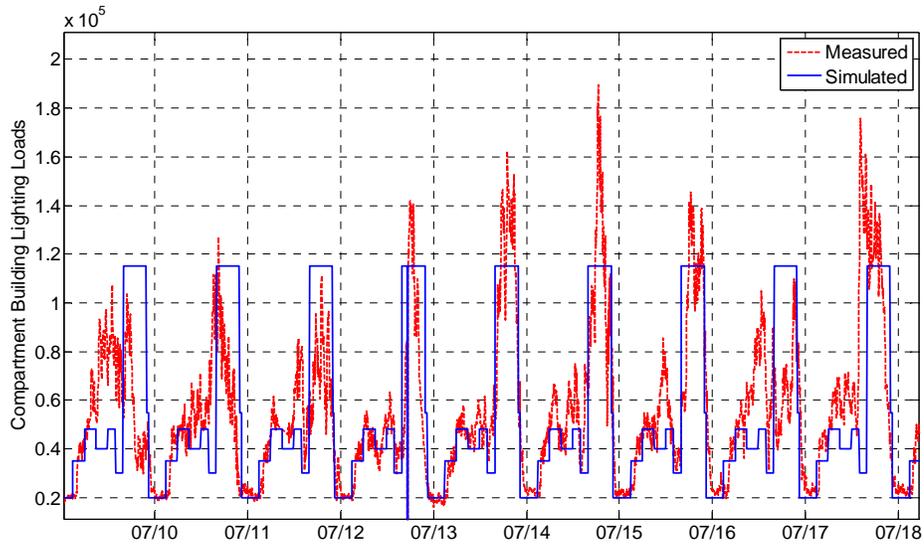


Figure A. 28 Comparisons between Measured and Estimated Plug Loads in Building 7114 from 07/09/2011 to 07/18/2011

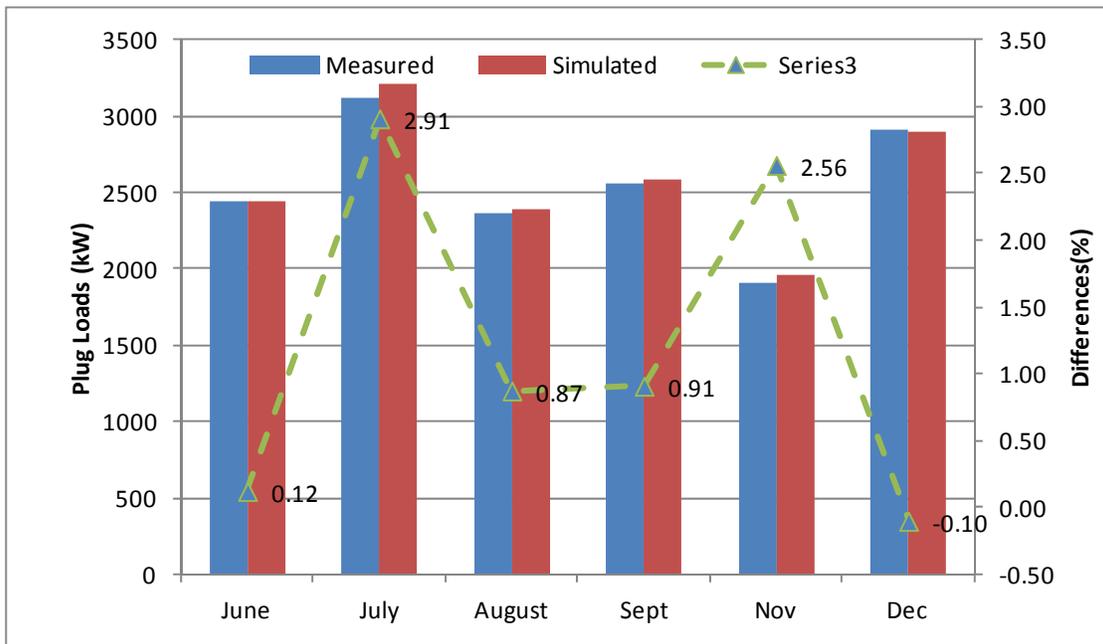


Figure A. 29 Comparisons between Measured and Estimated Plug Loads in Building 7114 from June to December, 2011.

### A.3 HVAC OPERATION SENSITIVITY STUDY ASSESSMENT

The HVAC operation sensitivity study was performed based on the integrated building envelope and HVAC equipment ROM. By comparing the existing operation baseline model with desired performance, the building energy consumption deviations were quantified.

#### *Case 1: Building 7230*

As the first step, the operation sensitivity study was performed for both heating and cooling seasons based on integrated system model for Building 7230. Two practical operation strategies were selected for the cooling season is: 1) pre-cooling; 2) chilled water supply temperature setpoint reset, while only pre-heating was selected for the heating season. The results are shown in Table A.4 below.

Table A.4 Results of Sensitivity Study for Cooling Season in Building 7230

<b>Energy Savings in July 2010</b>	<b>Option 1</b>	<b>Option 1 + 2</b>
Chiller Electricity	15.4%	18.1%
Whole Building Level Electricity	7.2%	8.2%
Peak Demand	12.5%	14.7%

Table A.4 shows that by pre-cooling only for July, the energy savings was 15.4% for the chiller electricity energy consumption, while 18.1% if both options were applied. The same magnitude of savings could be achieved for August, 2010 as well. This is due to the fact that the pre-cooling schedule results in a lower zone temperature before the occupied time so that the cooling system will not use as much cooling energy as the regular cooling schedule to cool down the space to the set-point. The peak demands were reduced by 12.5% and 14.7%, respectively. Table A.5 shows the results of the sensitivity study for the heating season. The energy savings was 5.4% and 2% for November 2010 and January 2011, respectively. These savings were smaller compared with savings opportunities in the cooling season because of the cold weather during the winter season in Chicago which downgrades the effects of the pre-heating. The peak demand reduction for those two months was 10.7% and 7.2%, respectively.

Table A.5 Results of Sensitivity Study for Heating Season with Pre-Heating Option Only

<b>Energy Savings</b>	<b>Nov 2010</b>	<b>Jan 2011</b>
Hot Water Energy Consumption	5.4%	2.0%
Peak demand	10.7%	7.2%

The sensitivity study also shows that the air-cooled chiller performance could be improved by 5-10% in terms of kW/ton.

#### *Case 2: Buildings 7113/7114*

Sensitivity of building thermal load to key control parameters has been evaluated for Buildings 7113/7114. Parameters varied are listed in Table A.6. Parameters of the baseline models, as shown in Table A.6, were set up based on the system in actual operation when the model was

created. Outdoor air damper was fully open in the cooling mode and was modulated to maintain the mixed air temperature so that is was not below 50 °F in the heating mode.

Table A.6 List of Parameters for Sensitivity Study of Buildings 7113/7114

Parameters	Baseline*	Variation
Cooling		
Option 1: Indoor Air Temperature Setpoint_Daytime (°F)	70	74
Option 2: Outdoor Air Fraction	100%	Economizer (Enthalpy Differential)
Heating		
Option 1: Indoor Air Temperature Setpoint_Daytime (°F)	72	68
Option 2: Minimum Outdoor Air Fraction	Varied to maintain ≥50 °F of mixed air temperature	30%

\*Taken from existing operational data

The study was performed with the integrated building system models calibrated with measured data of two typical cooling days, 7/7~7/8/2011, and two typical heating days, 12/8~12/9/2011. The impact on thermal loads is summarized in Table A.7 with adjustment of control setpoints as listed in Table A.6. Night setback control of indoor air temperature setpoint was also investigated. The result shown that night setback control did not have enough load reduction potentials for Building 7113/7114.

Table A.7 Results of Sensitivity Study of Buildings 7113/7114

		Building 7113		Building 7114	
Cooling	Options	1	1 + 2	1	1 + 2
	Load Reduction	16%	24%	18%	23%
Heating	Options	1	1 + 2	1	1 + 2
	Load Reduction	11%	12%	15%	39%

For the two buildings in the cooling mode, load could be reduced by 16~18% with indoor air temperature setpoint increased by 2.2 °C (4 °F). Load was reduced by 23~24% when outdoor air fraction was corrected from the observed wide open outdoor air damper to economizer operation, while the fan electricity consumption was reduced by 10 ~ 11%.

In the heating mode, thermal loads for both buildings were reduced with decreased indoor air temperature setpoint during the daytime and minimum outdoor air fraction. Load reduction of Building 7114 (39%) was more significant than Building 7113 (12%), which might have been caused by the distinct usage patterns between the two buildings during the heating season. As shown in Figure A.30, the lighting usage of Building 7113 was only half of Building 7114 during the heating season, which means some of the compartment zones were not used in Building 7113 during 2011 winter. This indicated during 2011 heating season the indoor air temperature setpoint (i.e., setpoint in unoccupied hours) in Building 7113 is lower than that (i.e., setpoint in

occupied hours) in Building 7114. Hence, Option 1 to change indoor air temperature setpoint had less effect on the thermal load reduction.

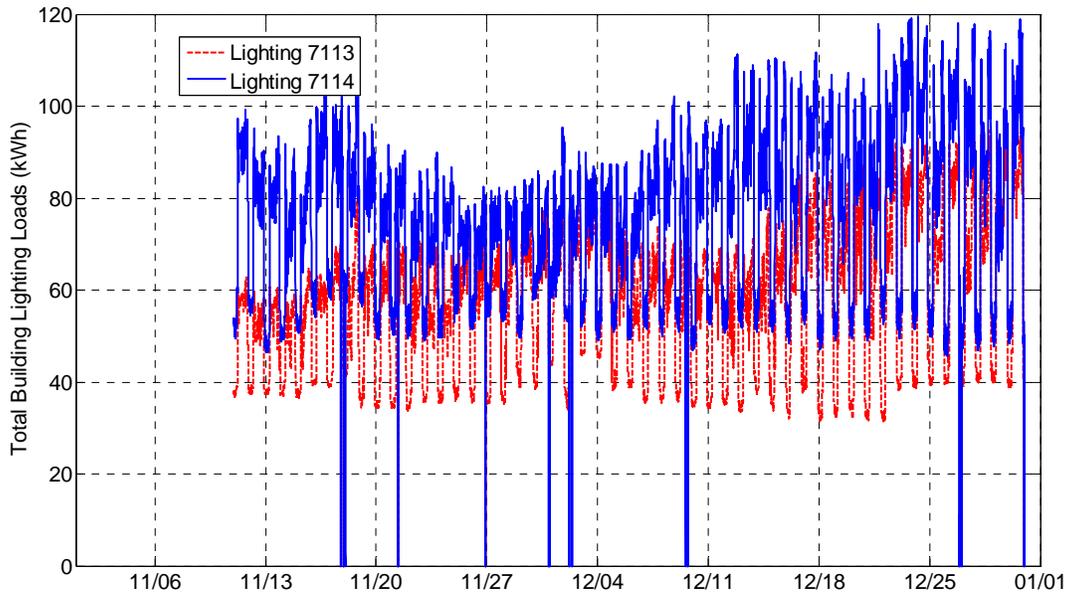


Figure A.30 Comparison of Measured Total Lighting Energy Consumption between Building 7113 and 7114.

The two-day evaluation results showed that building thermal load could be reduced by more than 10% with adjusted indoor air temperature setpoint and outdoor air fraction. Table A.7 shows that in average, building thermal load for Building 7113/7114 could be reduced by 23.5 to 25.5%. The primary energy usages (electricity and steam) are assumed to be reduced by at least 20% correspondingly.

With the options down-selected from the two-day study, HVAC operation sensitivity analysis was further extended to the seasonal operation for the cooling during June-July 2011 and for the heating during November-December 2011. Total cooling load was reduced by 44.9% with daytime indoor air temperature setpoint raised from 70 °F to 74 °F and outdoor air fraction reduced to 30% of total supply air flow rate. Total heating load decreased by 44.6% with daytime indoor air temperature setpoint lowered from 72 °F to 68 °F and outdoor air fraction reduced to 30% of total supply air flow rate.

This sensitivity study was intended to evaluate the variables with major impacts on building thermal loads. Savings might vary with practical limits of health, comfort or other operation constraints.

#### A.4 FAULT DETECTION AND DIAGNOSTICS PERFORMANCE ASSESSMENT

Below, representative FDD results were presented, and then followed by a brief analysis of the accuracy of the fault detection algorithms.

Case1: Building-level scheduling fault in Building 7230

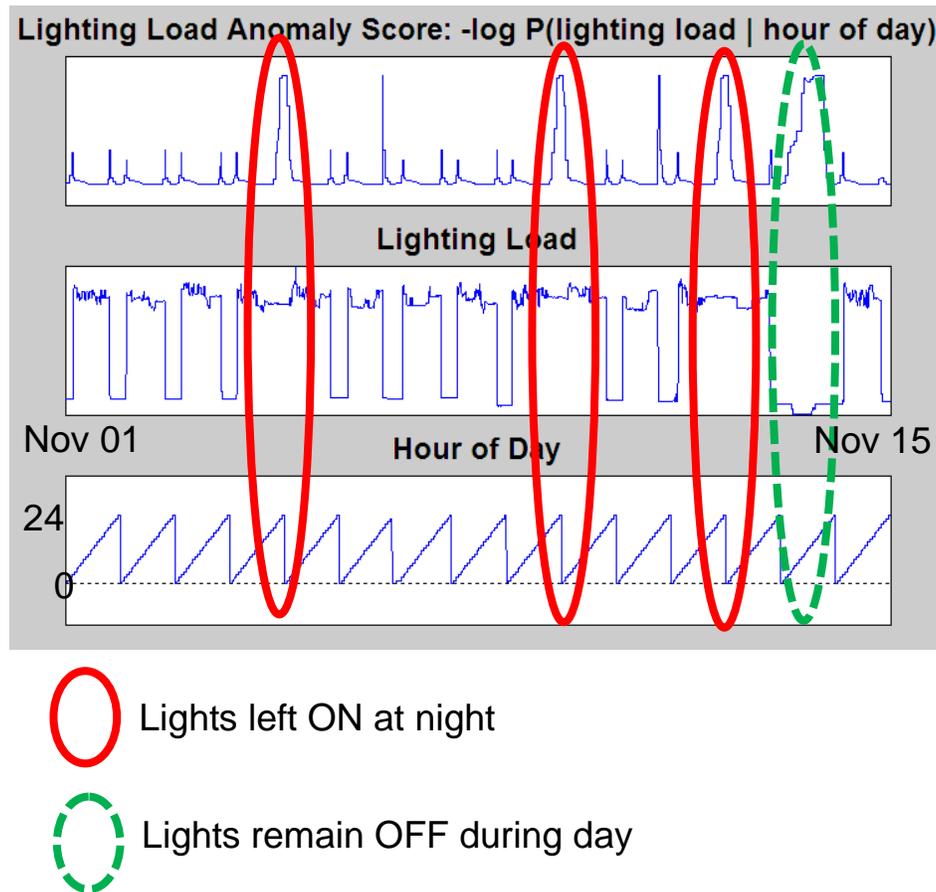


Figure A.31 Lighting Faults in Building 7230.

The top plot shows the anomaly score, the middle plot shows the lighting load and the bottom plot shows the hour of day. Highlighted in red are times when the lights were left on at night and highlighted in green are times when the lights were turned off during daytime.

Figure A.31 illustrates two kinds of anomalies detected in the lighting load of Building 7230 between 11/01/2011 and 11/15/2011. During this 15-day period, there were three instances detected when the lights were left on through the night (highlighted in red). There was also one instance detected when the lights were turned off during the day when the model expected them to be on (highlighted in green). The anomalies were based on a graphical network model that was trained on measured data from Building 7230.

Case 2: AHU 1 Economizer faults in Building 7114

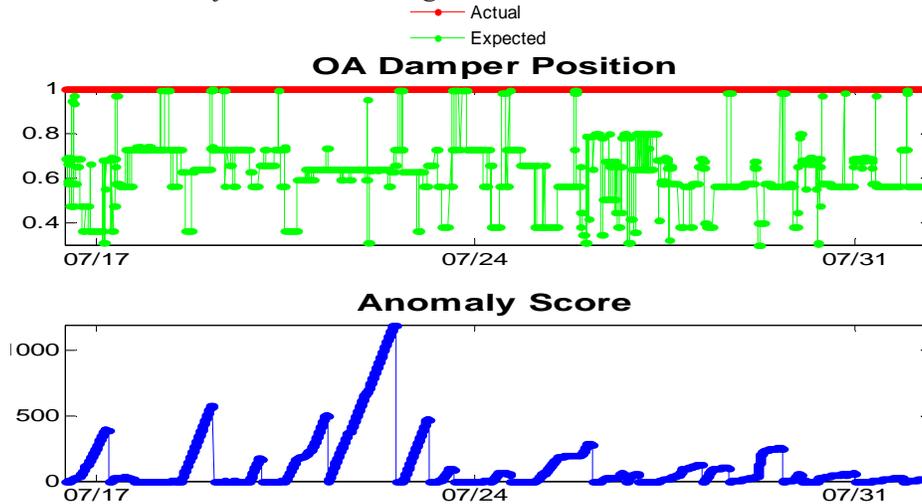


Figure A.32 AHU Economizer Fault in Building 7113/7114

The top panel in Figure A.32 shows the expected position of the damper in green and the measured damper position in red. Bottom panel shows the anomaly score. Notice that anomalies persist for most of this selected time period.

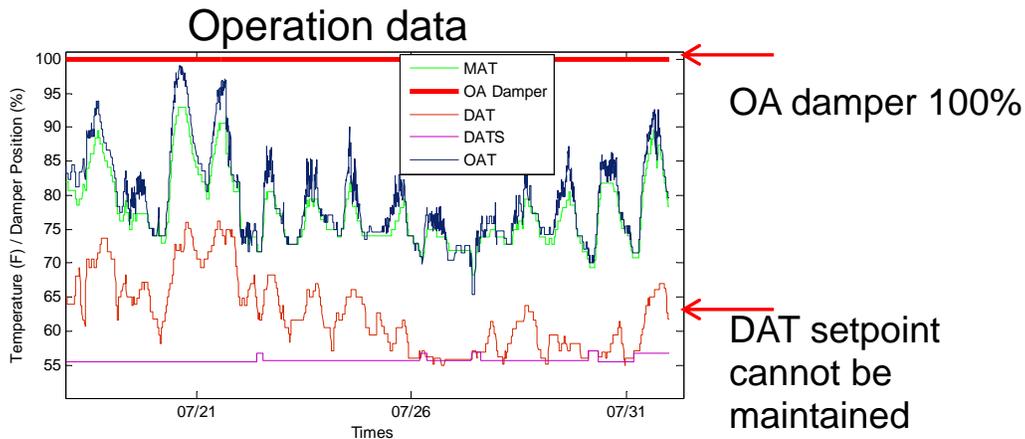


Figure A.33 AHU1 Faulty Operational data in July 2011

Figure A.33 above illustrates that the AHU operation fails to maintain the discharge air temperature (DAT) setpoint. While outside air temperature (OAT) was in the range of 80 °F to 100°F, the outside air damper was 100% open due to economizer faults.

Figures A.32 and A.33 show economizer operation faults in AHU 1 in Building 7114 in July, 2011. In this case, the outside air damper was expected to modulate but was open at 100% for the entire period. Further analysis showed that the enthalpy calculation in the control sequence was erroneous. This fault was detected and diagnosed on August 3<sup>rd</sup> based on a graphical network model as shown in Figure A.34. Since the team suspected that the economizer operation was not nominal, measured data was not used for training the graphical network corresponding to

nominal economizer operation. Instead, the results of the ROM were used for training the network. Once the network was trained, measured data was applied to generate anomaly scores. .

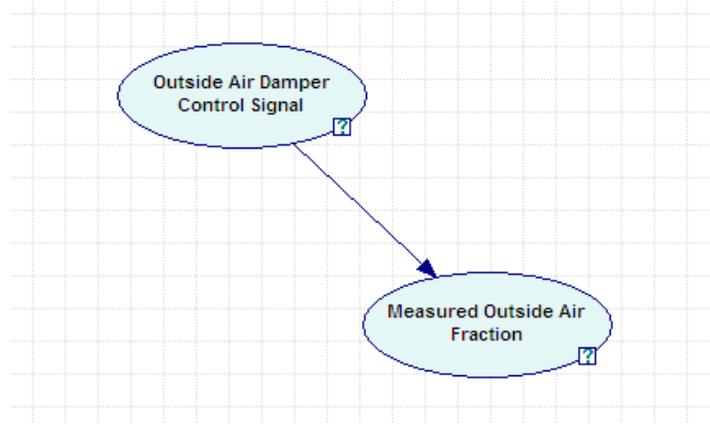


Figure A.34 Probabilistic Graphical Network for AHU1 Economizer

The diagnostics results were communicated and verified with the facility team. The faults were corrected on the same day. Figure A.35 shows the measured chilled water consumption vs. outside air temperatures for July and August in Building 7114. The chilled water BTU meter measurement confirmed 18% chilled water consumption reduction due to the corrected economizer faults. However, steam consumption reduction was not observed from the utility bill. This is probably due to the known issues for absorption chillers.

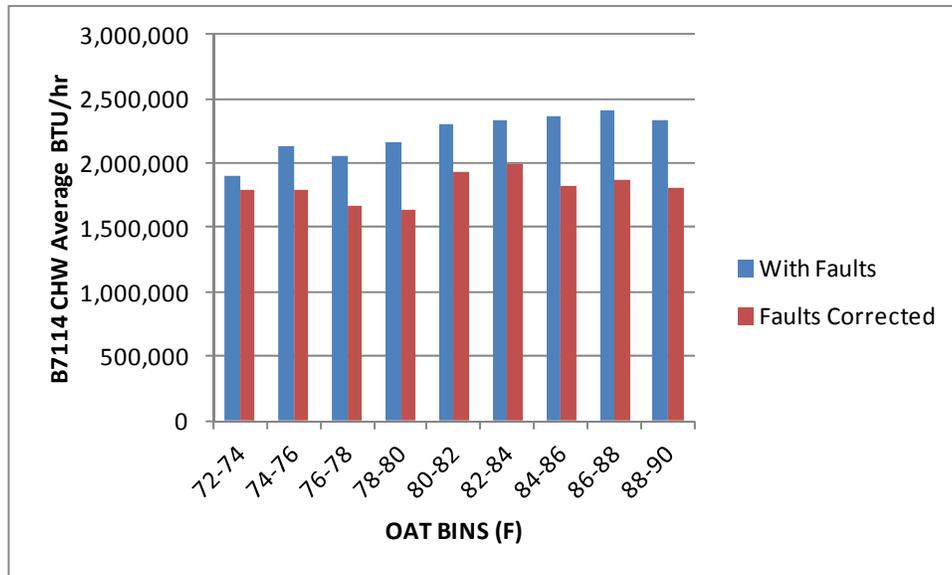


Figure A.35 Measured Chilled Water Consumption Comparisons

If this fault was not corrected on August 3<sup>rd</sup>, the annual chilled water consumption would be 18% more, as illustrated in Table A.8. The BIN method was used for the savings extrapolation with the assumption that the building will be in similar operation whenever outside air temperatures are similar.

Table A.8 Annual Chilled Water Consumption Extrapolation.

OAT BINS	Number of hrs*	Measured CHW consumption with fault (BTU/hr)	Measured CHW consumption with fault corrected (BTU/hr)	CHW consumption with fault (BTU)	CHW consumption with fault corrected (BTU/)
72-74	239	1,893,578	1,800,146	452,565,044	430,234,964
74-76	187	2,132,648	1,793,302	398,805,086	335,347,429
76-78	154	2,061,607	1,666,539	317,487,485	256,647,008
78-80	149	2,168,243	1,633,486	323,068,263	243,389,381
80-82	122	2,300,915	1,926,514	280,711,639	235,034,694
82-84	92	2,329,490	1,997,357	214,313,091	183,756,874
84-86	49	2,364,257	1,828,973	115,848,602	89,619,664
86-88	75	2,412,696	1,868,029	180,952,196	140,102,142
88-90	29	2,327,037	1,806,220	67,484,062	52,380,379
Total				2,351,235,469	1,966,512,534

\*Taken from TMY3 weather file for Wagkuan airport

*Case 3: Chiller faults in Building 7114*

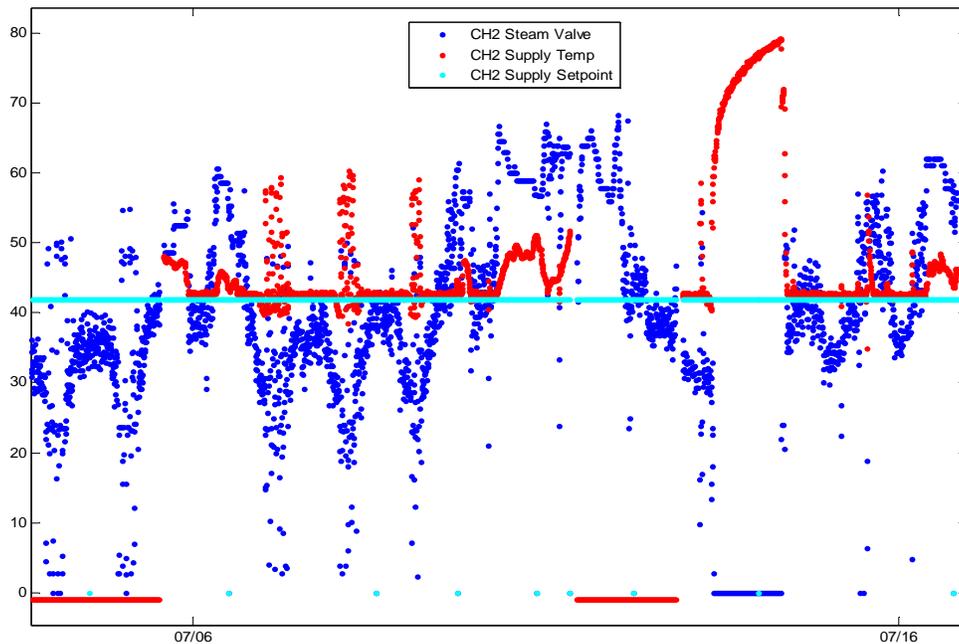


Figure A.36 Chiller 2 Faulty Operational Data in July 2011

Figure A.36 plots the steam valve position, supply water temperature and supply water temperature setpoint for Chiller 2 in Building 7114. In the first two weeks of July, Chiller 2 in Building 7114 could not maintain the supply water temperature setpoint intermittently as shown. Further analysis revealed that the issue was related to a faulty steam valve operation.

Case 4: Damper faults in a VAV Box in Building 7114

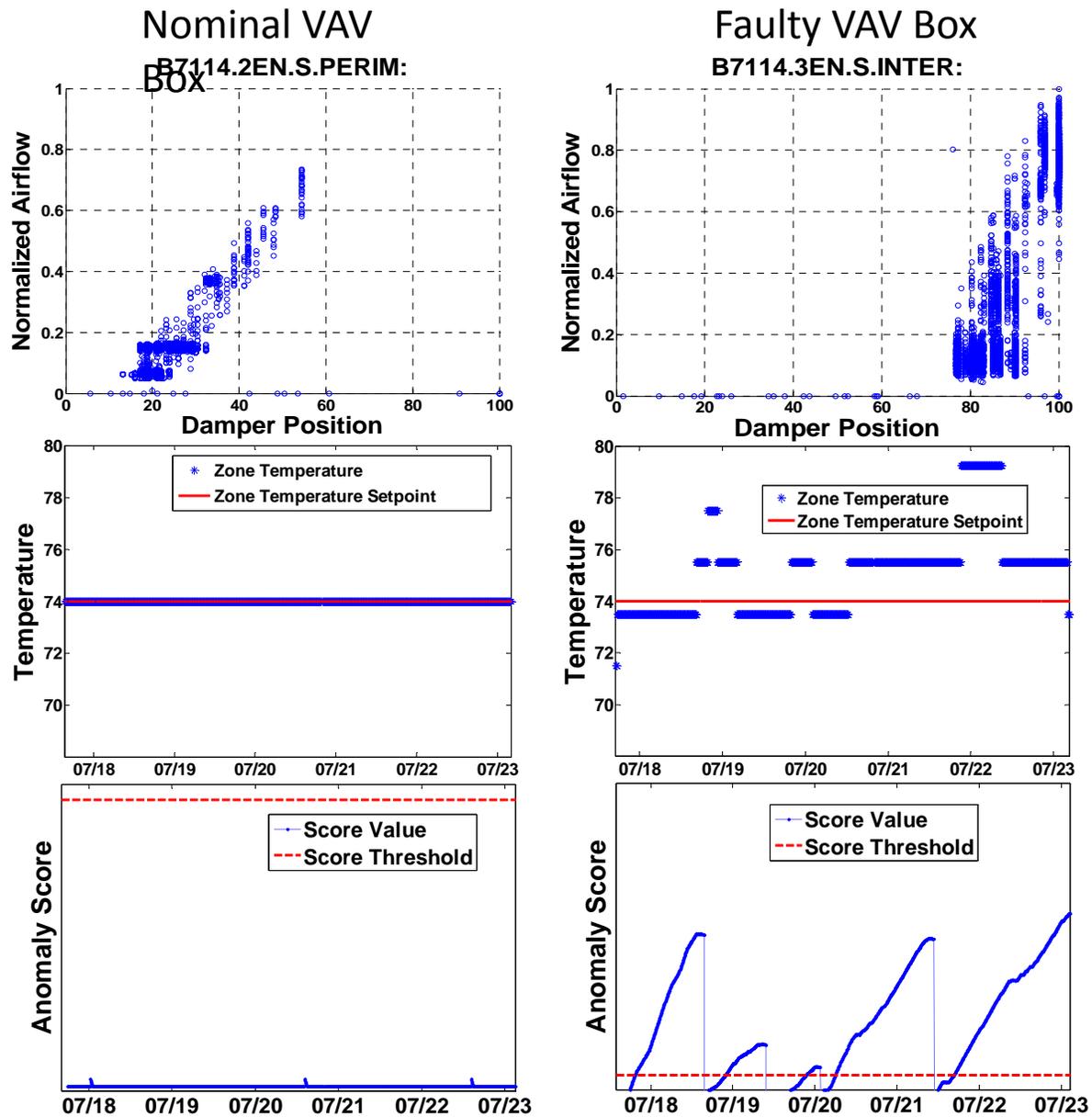


Figure A.37 VAV Box Fault Detection

In Figure A.37, plots on the left column indicate a normally operating airflow damper in a VAV box and plots on the right column show a faulty VAV airflow damper from Building 7114. The top row shows the relationship between the airflow and damper position. For the faulty VAV, notice that there is no airflow until the damper is opened beyond 80% indicating a “sticky damper.” As a result, the zone temperature setpoint cannot be maintained as illustrated in the middle row panel in Figure A.37. Shown in the bottom is the anomaly score that shows that the operation is anomalous for the entire selected time period.

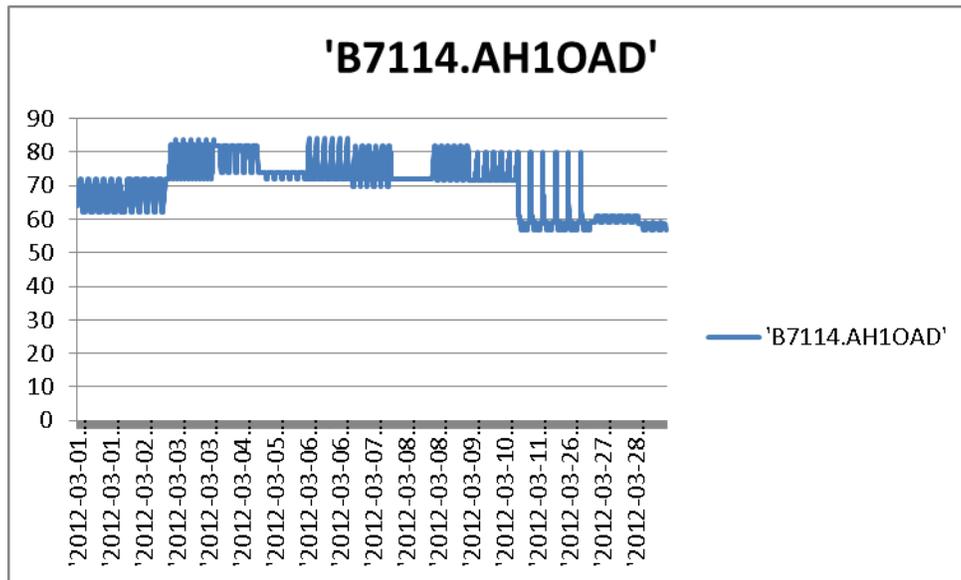
Figure A.37 illustrates the operation of two sample VAV boxes in Building 7114 over two weeks from July 2011. The VAV box “2EN.S.PERIM” operates normally while the VAV Box “3EN.S.INTER” is an example of faulty airflow damper operation. See the figure caption for more details about the fault.

*Accuracy Analysis*

To quantify the accuracy rate of the diagnostics algorithm, a dataset with known faults (*a priori*) is needed. Then, the algorithms can be applied to the dataset to quantify how many of the known faults were detected correctly.

The data from the AHU1 economizer in Building 7114 during March 1-31, 2012 was chosen. It was assumed that the outside air damper should operate at the minimal opening position whenever the AHU is in the heating mode (i.e., heating valve is open and hot water pump is ON). If the damper is not at the minimal position, then a fault is occurring and should be detected.

Since the team suspected that the economizer operation was not nominal, measured data was not used for training a graphical network corresponding to nominal economizer operation. The results of the integrated ROM for Building 7114 were used as training data for learning the network. Once the network was learned, measured data was applied to generate anomaly scores.



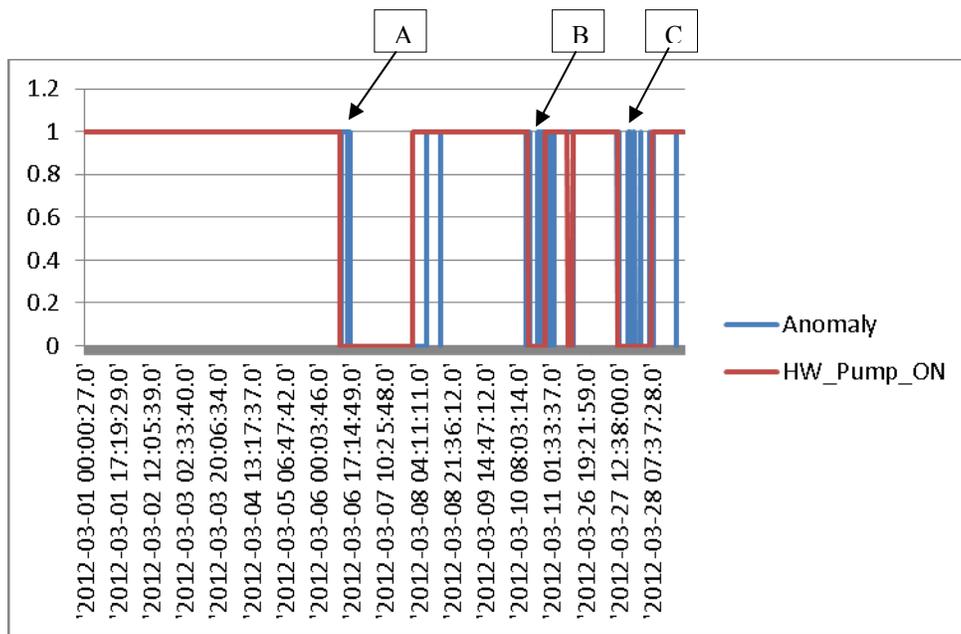


Figure A.38 Building 7114 AHU1 FDD Accuracy Analysis

The top panel in Figure A.38 displays the outside air damper position (OAD) for AHU1 in Building 7114. Notice that during the entire selected time period, the damper is never at the minimal position (30%). The bottom plot in Figure A.35 displays the anomaly status and the hot-water pump indicator.

The confusion matrix in Table A.9 shows the number of accurate classifications, missed detections and false alarms. This matrix contains information about actual and predicted classifications done by the proposed FDD method. True anomalies were detected correctly 2740 times out of 2843 actual anomalies corresponding to an accuracy of 96.38%. The no fault condition was detected correctly 612 times out of 781 times (78.36%). The false alarm rate was 21.64% and missed detection rate was 3.62%. During the selected time period, the outside air damper was never at the minimal position as shown in Figure A.34. Table A.9 shows the accuracy results.

Table A.9 Confusion matrix

	TRUE	FALSE	Total
TRUE	2740	103	2843
FALSE	169	612	781
Total	2909	715	3624

The false alarm rate at 21.64% was too high and further analysis was done to understand the drivers for this high false alarm rate. Regions when false alarms arise have been marked in the bottom panel of Figure A.38 as A, B and C. Notice that false alarms in Region A occur right after the HW pump was turned off. If we take into account potential residual flow right after the pump was turned off and ignore these alarms from Region A as false alarms, the false alarm rate

drops to 15.11%. From the perspective of finding entire fault periods, it can be noticed that false alarms in both Region A and Region B occur contiguous to true fault periods. Ignoring false alarms in both these regions, the false alarm rate further drops to 5.63%.

#### A.5 ENERGY SAVINGS OPPORTUNITIES ASSESSMENT

Savings calculations were based on: 1) identified percentage savings described in Appendices A.3 and A.4 and 2) building utility bill and metering data in 2011. Tables A.10 and A.11 show the steam and electricity bills for Building 7113/7114.

Table A.10 Building 7113/7114 Steam Utility Bill in 2011

2011	B7113 steam (MMBTU)	B7114 steam (MMBTU)
Jan-11	729.7	3221.2
Feb-11	612.0	3124.3
Mar-11	743.2	2937.2
Apr-11	841.8	2098.4
May-11	834.6	1802.4
Jun-11	718.0	1812.8
Jul-11	571.8	871.5
Aug-11	571.3	2034.6
Sep-11	691.6	2575.7
Oct-11	533.0	1226.8
Nov-11	427.3	1358.2
Dec-11	541.1	1971.1

Table A.11 Building 7113/7114 Electricity Utility Bill in 2011

	B7113 electricity 208V (KWh)	B7113/B7114 electricity 408V (KWh)	B7114 electricity 208 V (KWh)
Jan-11	40080	284880	41280
Feb-11	35760	273600	38400
Mar-11	39840	273840	40320
Apr-11	38400	241920	35040
May-11	37920	226560	37920
Jun-11	35760	231360	44640
Jul-11	34800	217920	30960
Aug-11	37200	301680	40560
Sep-11	50160	310560	50640
Oct-11	39600	234480	43680
Nov-11	33600	171360	32160
Dec-11	30240	165360	32160

Both absorption chillers and steam-to-hot water heat exchangers are located in Building 7114, and the only steam end use in Building 7113 is domestic hot water. The domestic hot water

usages are assumed to be the same for Buildings 7113 and 7114. Therefore, the total annual HVAC related steam consumption for Building 7113/7114 was assumed to be 17,218.8 MMBTU in 2011. Absorption chillers were only turned on from April to October and consumed 17% of the total steam. Heating related steam consumption was about 35% of the total. Figure A.39 illustrates steam end use in Building 7113/7114.

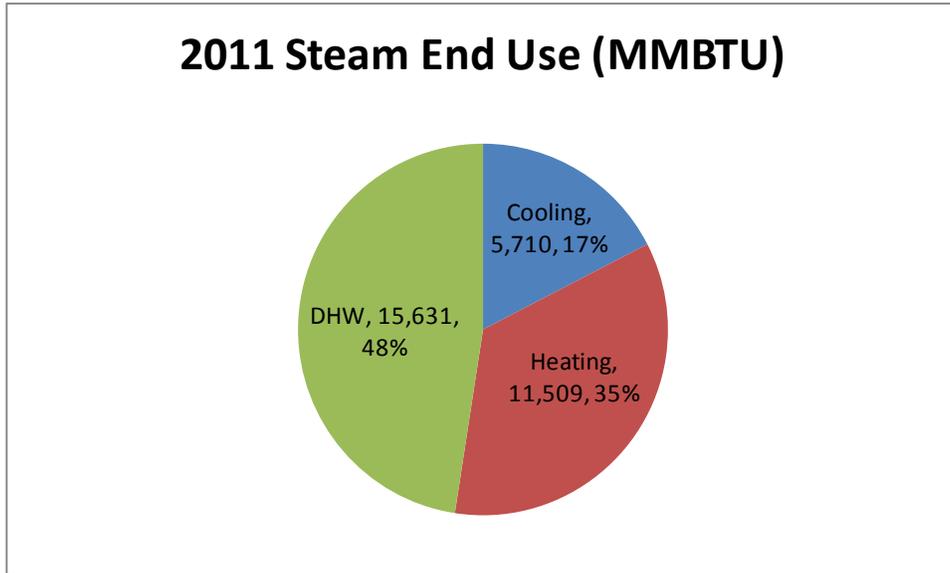


Figure A.39 Building 7113/7114 Steam End Use in 2011

From the lighting and plug load sub-meters deployed in Building 7113/7114 by this demonstration project, together with the utility bill, HVAC related electricity end use can be calculated. Figures A.40 and A.41 show the electricity end use for Building 7113/7114 in July and December 2011, respectively. 43% of annual electricity consumption was assumed to be from HVAC equipment including pumps and fans for further energy savings analysis.

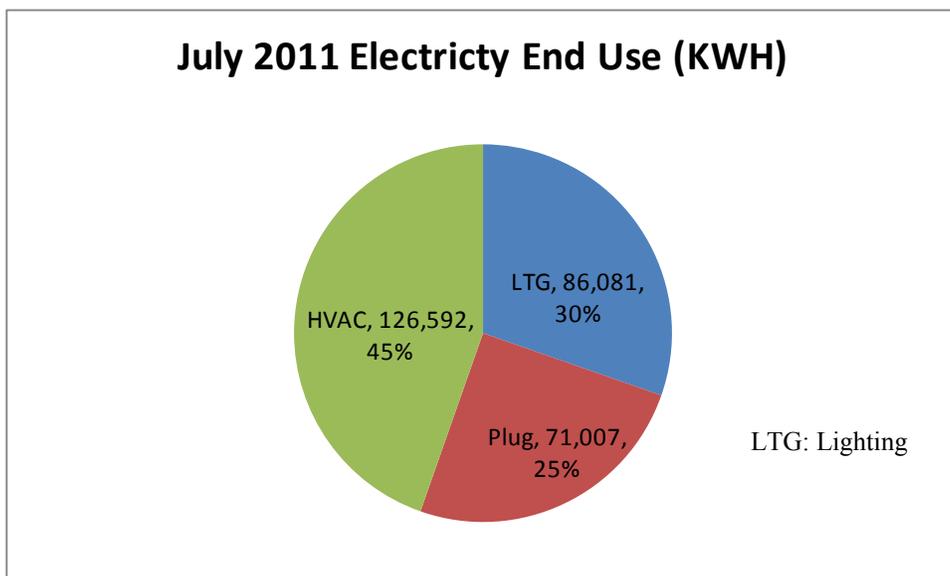


Figure A.40 Building 7113/7114 Electricity End Use in July 2011

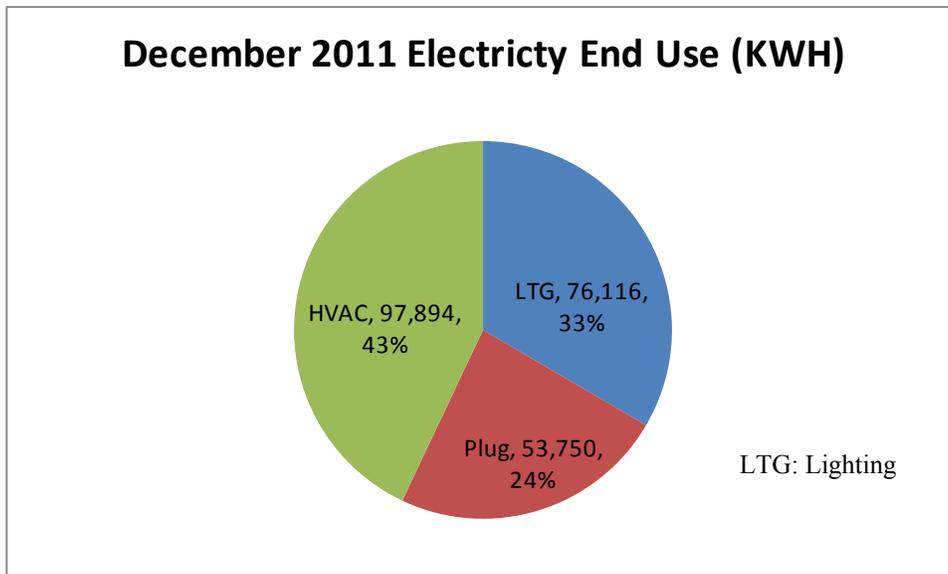


Figure A.41 Building 7113/7114 Electricity End Use in December 2011

For Building 7113/7114 savings calculations, the following assumptions are used:

- Based on 2011 utility bill
- 17% annual steam consumption is from the cooling
- 35% annual steam consumption is from the heating
- 43% annual electricity consumption is from the HVAC equipment and system
- 20% annual energy savings from the deployment of the aBEMS. Please refer to Table A.7 in Appendix A.3 for savings number<sup>20</sup>.
  - Economizer faults correction
  - HVAC operation sensitivity study (setpoint reset and outside air flow rate control)

Table A.12 lists breakdown energy savings for Building 7113/7114.

Table A.12 Building 7113/7114 Energy Savings

	2011 Total	20% Savings
Cooling steam (MMBTU)	5,709.70	1,141.94
Heating steam (MMBTU)	11,509.10	2,301.82
HVAC Electricity (kWh)	1,657,495.20	331,499.04

## A.6 TECHNOLOGY SCALABILITY ASSESSMENT

First, the scalability of demonstrated technology was assessed by the implementation time (i.e., labor hours) for the different technology elements:

<sup>20</sup> The savings from correcting economizer faults was included in option 2 of HVAC operation sensitivity study. The existing operation baseline used in the sensitivity study reflected the faulty operation.

- Time to create ROM building envelope models was reduced by 50%-75% by using the toolkit to automatically convert from BIM to BEM compared with the traditional method to create detailed building models.
- The time to create the HVAC equipment model using the ROM model library is varied (up to 50% reduction) depending on the data availability and quality for given equipment
- For the HVAC equipment and system with the same configuration, the probabilistic graphical model based energy diagnostics requires 50% less labor time as diagnostic models can be directly re-used.
- For similar HVAC equipment and systems, the probabilistic graphical model based energy diagnostics takes 10-20% less labor time as the graphical structure does not have to be learned from data and validated by experts. The networks have to be trained however to obtain appropriate parameters.

The toolkits, model developments and diagnostics algorithms testing occurred at the same time when the demonstrations in Building 7230 and Building 7113/7114 were conducted. Therefore, it is impossible to do a fair evaluation of the implementation time for the demonstrated technology in these buildings. However, if assuming all the toolkits and algorithms are in place, the implementation time of the aBEMS will be at least 30% less for Building 7113/7114 compared with Building 7230 mainly due to:

- Reusable building envelope and HVAC equipment ROM library;
- A toolkit to automatically transfer a BIM to a BEM;
- Scalable probabilistic graphical model based energy diagnostics.

The aBEMS was successful implemented in buildings with different use types and different sizes (Building 7230: drill hall and office building with 70,000 ft<sup>2</sup> vs. Building 7113/7114: barracks building with 300,000 ft<sup>2</sup>).

## **APPENDIX B: BUILDING LIFE CYCLE COST MODEL RESULTS**

The MILCON ECIP template in the NIST BLCC program [20] is used to calculate the SPB (Simple Payback) and SIR (Savings to Investment Ratio) for the advanced building energy management system in Building 7113/7114.

Section 5 and Appendix A provide details of savings opportunities from the demonstration buildings. It is assumed that there will be ~\$1,000 savings per year per building for operation and maintenance costs due to the fact that the system down-time could be reduced and the facility team could better prioritize their work orders. The following assumptions are used:

- \$0.069/kWh for electricity and \$8.7 /MMBTU for steam
- No demand charge
- Real discount rate of 3%
- Inflation rate of 1.2%
- Length of study period is 10 years

Below is the output of the BLCC model for the aBEMS demonstration in Building 7113/7114:

## NIST BLCC 5.3-09: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A  
 The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2009.

Location: Illinois Discount Rate: 3%

Project Title: BLDG7114 Analyst:

Base Date: April 1, 2010 Preparation Date: Mon Sep 17 12:03:58 EDT 2012

BOD: April 1, 2011 Economic Life: 10 years 0 months

File Name: C:\Program Files\BLCC5\projects\G1\_BLDG7114.xml

### 1. Investment

Construction Cost	\$150,129
SIOH	\$0
Design Cost	\$0
Total Cost	\$150,129
Salvage Value of Existing Equipment	\$0
Public Utility Company	\$0
Total Investment	\$150,129

### 2. Energy and Water Savings (+) or Cost (-)

#### Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	\$11.64871	4,574.9 MBtu	\$52,834	7.924	\$418,644
Energy Subtotal		4,574.9 MBtu	\$52,834		\$418,644
Water Subtotal		0.0 Mgal	\$0		\$0
Total			\$52,834		\$418,644

### 3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Non-Annually Recurring				
training	-\$1,000	0 years 0 months	0.971	-\$971
Non-Annually Recurring Subtotal	-\$1,000			-\$971
Total	-\$1,000			-\$971

4. First year savings \$52,734

5. Simple Payback Period (in years) 2.85 (total investment/first-year savings)

6. Total Discounted Operational Savings \$417,673

7. Savings to Investment Ratio (SIR) 2.78 (total discounted operational savings/total investment)

8. Adjusted Internal Rate of Return (AIRR) 14.10%  $(1+d)*SIR^{(1/n)}-1$ ; d=discount rate, n=years in study period

## APPENDIX C: MANAGEMENT AND STAFFING

The Table C.1 and Figure C.1 below show the organization chart for the project.

Table C.1 Point of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Trevor Bailey	United Technologies Research Center 411 Silver Lane, MS 129-78 East Hartford, CT, 06118	Ph. (860) 610-1554 Fax (860) 660-1014 Email: BaileyTE@utrc.utc.com	Project Leader
Zheng O'Neill	United Technologies Research Center 411 Silver Lane, MS 129-85 East Hartford, CT, 06118	Ph. (860) 610-7331 Fax (860) 622-6228 Email: O'NeillZ@utrc.utc.com	Co-PI
Peter Behrens	Public Works Department, Great Lakes 2625 Ray Street Great Lakes, IL 60088-3147	Ph. (847) 688-2121 x28 Fax: 847-688-2124 Email: peter.behrens@navy.mil	Navy Great Lakes Energy Manager

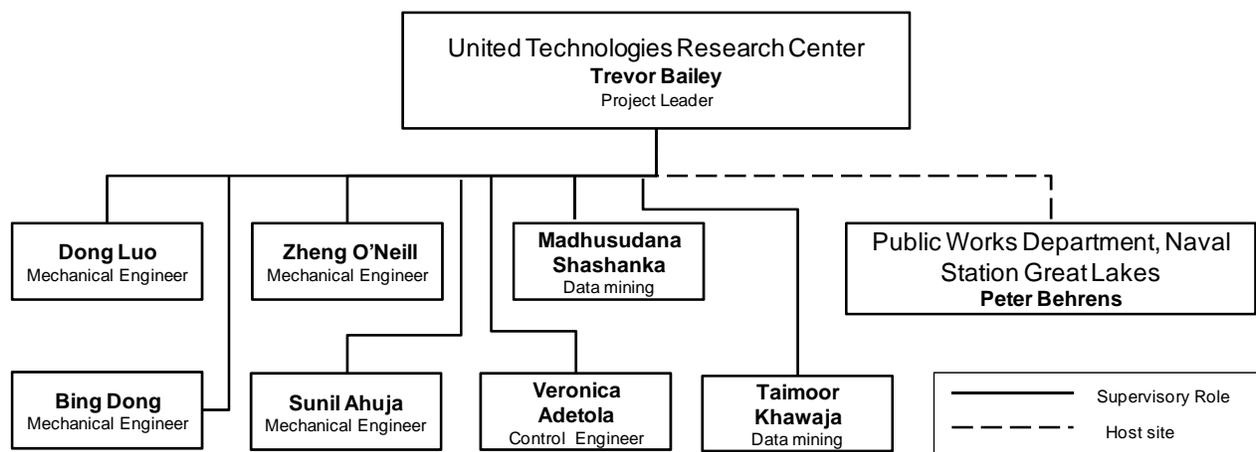


Figure C.1 Organization Chart

## APPENDIX D: REFERENCE

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## APPENDIX E: REDUCED-ORDER BUILDING ENVELOPE MODEL

### 1. Overall Reduced-order Building Envelope Model

The heat balance includes the solar radiation on the external surface of the structure, the transmitted solar radiation through the windows and subsequently absorbed by interior walls, floors and furniture, air leakage through doors, sensible air from HVAC, and sensible loads due to lighting, people and equipment. The mass balance includes refrigerator cases generated or removed humidity, water vapor brought by HVAC supply air and latent loads due to people and equipment.

The thermal network model has been widely used to represent the above heat transfer and thermal dynamics process through building envelope and the subsequent effects on indoor air temperature. In this study this method was adopted. Two major assumptions were used for a given zone:

- The zone air and humidity is well mixed
- Longwave radiation exchanges between surfaces are not considered.

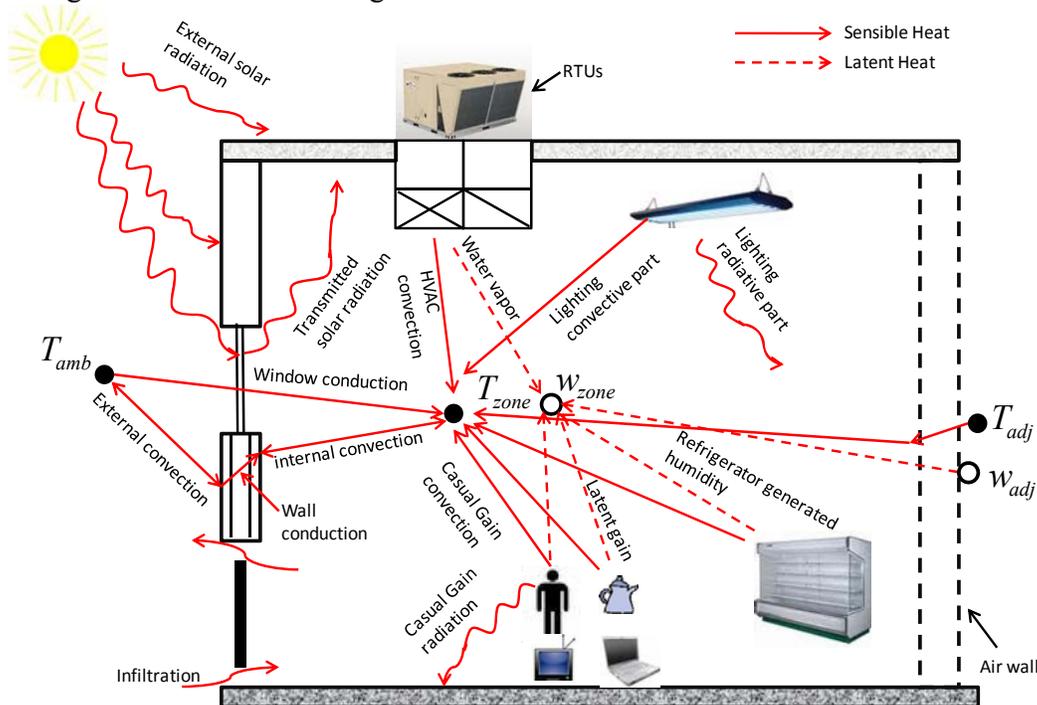


Figure E.1 Energy Flow in Buildings for ROM

Figure E.1 shows a typical energy flow in buildings for ROM. The energy balance in one zone with one air node can be described as:

$$m_{air\_zone} \frac{dH_{zone}}{dt} \quad (1)$$

$$= \dot{m}_{sup} (H_{SUP} - H_{zone}) + \dot{m}_{inf} (H_{AMB} - H_{zone}) + Q_{int} + \sum_i^{N_{surface}} Q_{structure\_i} +$$

$$\sum_{i=1}^{N_{adjzone}} \dot{m}_{zonei} (H_{zonei} - H_{zone}) + \dot{m}_v C_{pv} T_{zone}$$

$$H_{zone} = T_{zone} (C_{pa} + \omega_{zone} C_{pv}) \quad (2)$$

$$H_{SUP} = T_{sa} (C_{pa} + \omega_{sa} C_{pv}) \quad (3)$$

$$H_{AMB} = T_{AMB} (C_{pa} + \omega_{AMB} C_{pv}) \quad (4)$$

$$H_{zonei} = T_{zonei} (C_{pa} + \omega_{zonei} C_{pv}) \quad (5)$$

Where

$H_{zone}$ ,  $H_{SUP}$ ,  $H_{AMB}$  and  $H_{zonei}$  are enthalpies of zone air, supply air, outdoor air and adjacent zone air respectively

$m_{air\_zone}$  air mass for the given zone [kg];

$C_{pa}$  specific heat capacity of dry air [J/kg/°C];

$C_{pv}$  specific heat capacity of water vapor [J/kg/°C];

$T_{zone}$  zone air temperature [°C];

$T_{SUP}$  supply air temperature [°C];

$\dot{m}_{sup}$  supply air mass flow rate [kg/s];

$\dot{m}_{inf}$  Infiltration mass flow rate [kg/s];

$\dot{m}_v$  Internal water vapor generation rate [kg/s];

$Q_{int}$  convective internal loads[W];

$\sum_i^{N_{surface}} Q_{structure\_i}$  sum of the convective heat transfer between the zone air and zone's internal surface temperature [°C];

$\sum_{i=1}^{N_{adjzone}} (H_{zonei} - H_{zone})$  sum of the enthalpy exchange due to interzone air mixing;

$\dot{m}_{inf} (H_{AMB} - H_{zone})$  enthalpy exchange due to infiltration/leakage of outside air;

The mass balance equation of water vapor in a zone is given by:

$$m_{air\_zone} \frac{d\omega_{zone}}{dt} = \dot{m}_{SUP} (\omega_{sa} - \omega_{zone}) + \dot{m}_v + \sum_{i=1}^{N_{adj}} \Delta \dot{m}_i (\omega_{zonei} - \omega_{zone}) \quad (6)$$

Where

- $\omega_{sa}$  humidity ratio of supply air flow [kg/kg]
- $\omega_{zone}$  humidity ratio of the given zone [kg/kg]
- $\omega_{zonei}$  humidity ratio of adjacent zones [kg/kg]

Since there are open refrigerator cases and cooking area in this supermarket, the humidity and water vapor generation at the zone level cannot be neglected.

The 3R2C thermal network model is used for estimating building structure load as shown in Figure E.2.

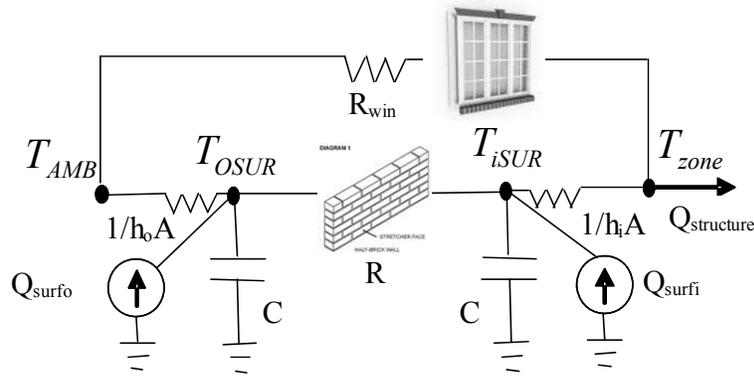


Figure E.2 Thermal Network Model of One External Wall

The heat balance equation for outside surface is given by:

$$C \frac{dT_{osurf}}{dt} = h_o A (T_{amb} - T_{osurf}) + \frac{T_{isurf} - T_{osurf}}{R_{wall}} + Q_{surfo} \quad (7)$$

The heat balance equation for inside surface is given by:

$$C \frac{dT_{isurf}}{dt} = h_i A (T_{zone} - T_{isurf}) + \frac{T_{osurf} - T_{isurf}}{R_{wall}} + Q_{surfi} \quad (8)$$

The heat balance equation for the zone air node is given by:

$$Q_{structure} = h_i A (T_{isurf} - T_{zone}) + \frac{(T_{amb} - T_{zone})}{R_{win}} \quad (9)$$

The solar radiation on external and internal surfaces is defined as:

$$Q_{surfo} = \alpha Q_{sol} \quad (10)$$

$$Q_{surfi} = \beta Q_{sol} + \gamma Q_{int} \quad (11)$$

The thermal resistance and capacity are defined as:

$$R = \frac{l}{kA}, C = \frac{\rho C_p l A}{2} \quad (12)$$

Where,

$T_{isurf}$	inside surface temperature [°C]
$T_{osurf}$	outside surface temperature [°C]
$Q_{surfo}$	outside surface absorbed solar radiation [W]
$Q_{surfi}$	inside surface absorbed solar radiation [W]
$h_o$	outside surface heat transfer coefficient [W/m <sup>2</sup> , °C]
$h_i$	Inside surface heat transfer coefficient [W/m <sup>2</sup> , °C]
$A$	wall or window surface area [m <sup>2</sup> ]
$k$	thermal conductivity of surface [W/m, °C]
$\rho$	density of the surface material [kg/m <sup>3</sup> ]

## 2. Solar Radiation Model

The solar radiation model is based on Chapter 14, ASHARE Fundamentals. For the total amount of solar radiation on a receiving surface, there are three steps.

Step 1: Calculate the sun position

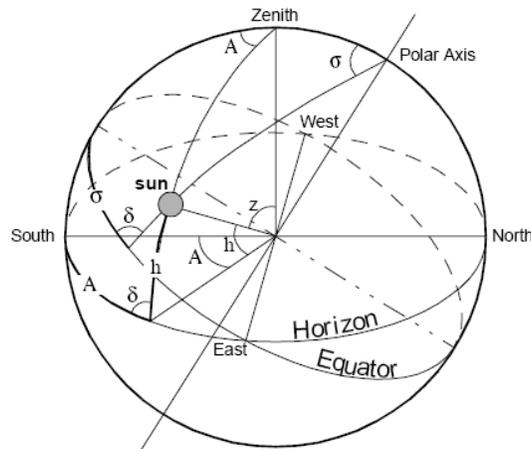


Figure E.3 Sun Position in An Earth-Sun System

Solar altitude  $h$  and solar azimuth  $A$  are used to describe the position of the Sun relative to the earth. Solar altitude and azimuth angles  $h$ , in turn, depend on the local latitude  $L$  (°N, negative in the southern hemisphere); the solar declination  $\delta$ , which is a function of the date; and the hour angle  $H$ , defined as the angular displacement of the sun east or west of the local meridian due to the rotation of the earth, and expressed in degrees as:

$$H = 15(AST - 12) \quad (13)$$

where  $AST$  is the apparent solar time. Now the relationship of solar altitude is defined as:

$$\sin(h) = \cos(L) \cos(\delta) \cos(H) + \sin(L) \sin(\delta) \quad (14)$$

The azimuth angle is uniquely defined by its sine and cosine given below:

$$\sin(A) = \sin(H) \cos(\delta) / \cos(\beta) \quad (15)$$

$$\cos(A) = (\cos(H) \cos(\delta) \sin(L) - \sin(\beta) \cos(L)) / \cos(\beta) \quad (16)$$

### Step 2: Geometry information of receiving surface

The orientation of a receiving surface is best characterized by its tilt angle and its azimuth. The tilt angle  $\Sigma$  (also called slope) is the angle between the surface and the horizontal plane. Its value lies between 0 and 180°. Most often, slopes are between 0° (horizontal) and 90° (vertical). Values above 90° correspond to surfaces facing the ground. The surface azimuth  $\psi$  is defined as the displacement from south of the projection, on the horizontal plane, of the normal to the surface.

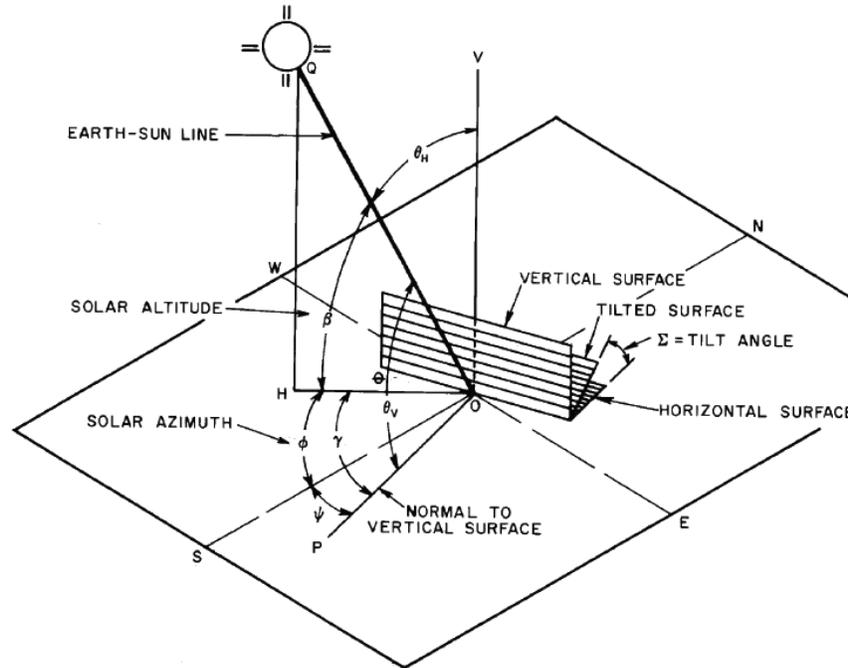


Figure E.4 Solar Angle for Vertical and Horizontal Surfaces [1]

The surface-solar azimuth angle  $\gamma$  is defined as the angular difference between the solar azimuth  $A$  and the surface azimuth  $\psi$

$$\gamma = A - \psi \quad (17)$$

Finally, the angle between the line normal to the irradiated surface and the earth-sun line is called the angle of incidence  $\theta$ . It is important in fenestration, load calculations, and solar technology because it affects the intensity of the direct component of solar radiation striking the

surface and the surface's ability to absorb, transmit, or reflect the sun's rays. Its value is given by:

$$\cos(\theta) = \cos(h) \cos(\gamma) \sin(\Sigma) + \sin(h) \cos(\Sigma) \quad (18)$$

Step 3: Calculate solar radiation on the receiving surface

Total sky irradiance  $S_g$  reaching the receiving surface is the sum of three components: the beam component  $S_{beam}$  originating from the solar disc; the diffuse component  $S_{diff}$  originating from the sky dome; and the ground-reflected component  $S_{ref}$  originating from the ground in front of the receiving surface. Thus,

$$S_g = S_{beam} + S_{diff} \quad (19)$$

Normally, the  $S_{beam}$  and  $S_{diff}$  are from measurements.

### 3. Infiltration Model

Air infiltration through the building envelope has a significant impact on the space heating energy use in buildings. Although there are very detailed and complex approaches available to model air infiltration using air flow networks (AFN) and computation fluid dynamics (CFD), typically building energy simulation tools use a simplified approach to estimate air change rate based on building air tightness measured by pressurization tests. Several field surveys and test methods have been developed to specify building level air infiltration rates for a known standard pressure difference across the envelope. In an effort to specify air-barrier requirements, the ASHRAE 90.1 Envelope Subcommittee has developed a list of component infiltration rates that can be used to calculate the overall building air infiltration rate. During the development of air barrier requirement changes to 90.1-2004, ASHRAE SSPC 90.1 Envelope Subcommittee developed recommendations of baseline and advanced infiltration levels for building components, as shown in Table E.1 [2]. These recommendations were provided for each opaque element of the envelope such as walls, windows, roof, etc. The total infiltration for a building can be calculated by aggregating the component infiltration rates.

During the HVAC design, there is a design criterion for indoor-outdoor air pressure difference, for example 75 pa. Based on this assumption, there is a method to convert this into wind-driven infiltration model, which is called design flow rate model.

$$Infiltration = I_{design} [A + B * |T_{zone} - T_{ambient}| + C(WindSpeed) + D(WindSpeed^2)] \quad (20)$$

Where coefficients A,B,C and D are different for different models as shown in Table E.2 [2] below.

Table E.1 Envelope Component Infiltration Rates

<b>Component Infiltration Rate Summary Table</b> (SSPC 90.1 Envelope Subcommittee)					
Opaque Elements	Baseline Infiltration Rate (@ 0.30 in. w.c.)	Addenda 'z' Infiltration Rate (@ 0.30 in. w.c.)	Unit	Area calculation notes	Reference
Roofs	0.12	0.04	cfm/sf	Net opaque area of roof	Envelope Subcommittee
Above Grade Walls	0.12	0.04	cfm/sf	Net opaque area of above grade walls	Envelope Subcommittee
Below Grade Walls	-	-	-	Not used in infiltration calculations	-
Floor	0.12	0.04	cfm/sf	Net opaque area of floor over unconditioned space	Envelope Subcommittee
Slab	-	-	-	Not used in infiltration calculations	-
Opaque Doors	0.40	0.40	cfm/sf	Area of opaque doors	90.1-2004 Section 5.4.3.2
Loading Dock Doors	0.40	0.40	cfm/sf	Area of door, applicable only for warehouses	90.1-2004 Section 5.4.3.2
<b>Fenestration Elements</b>					
Swinging or Revolving Glass Doors	1.00	1.00	cfm/sf	Area of swinging or revolving glass doors	90.1-2004 Section 5.4.3.2
Vestibule	1.00	1.00	cfm/sf	Area of door	90.1-2004 Section 5.4.3.2
Sliding Glass Doors	0.40	0.40	cfm/sf	Area of sliding glass doors	90.1-2004 Section 5.4.3.2
Windows	0.40	0.40	cfm/sf	Area of windows	90.1-2004 Section 5.4.3.2
Skylights	0.40	0.40	cfm/sf	Area of skylights	90.1-2004 Section 5.4.3.2
Construction Quality Adjustment (CQA <sup>1</sup> )	CQA=Total Building Leakage –(∑ component infiltration rates)		cfm/sf	To be calculated for each building type	Envelope Subcommittee
<b>Total Building Leakage<sup>2</sup></b>	<b>1.8</b>	<b>CQA + component infiltration rates</b>	<b>cfm/sf</b>	<b>exterior above grade envelope surface area</b>	<b>NIST REPORT NISTIR 7238</b>

Table E.2 Infiltration Coefficients

Model Name	Constant Coefficient (A)	Temperature Coefficient (B)	Wind Speed Coefficient (Linear term) (C)	Wind Speed Coefficient (Quadratic term) (D)	Reference Wind Speed
Constant Infiltration (EnergyPlus default)	1.0	0	0	0	N.A.
DOE-2 Infiltration Methodology	0	0	0.224	0	10 mph
BLAST Infiltration Methodology	0.606	0.03636	0.1177	0	7.5 mph

The designed infiltration is defined as:

$$I_{design} = (\alpha_{bldg} + 1) \times I_{75pa} \left( \frac{0.5C_s \rho U_H^2}{75} \right)^n \quad (21)$$

Where  $\alpha_{bldg}$  is the atmospheric boundary layer component. For a typical urban terrain environment,  $\alpha_{bldg}$  is 0.22.  $C_s$  is the local wind pressure coefficient at the point of impingement.  $U_H$  is the wind speed at building height and defined as:

$$\frac{U_H}{U_{met}} = \left(\frac{\delta_{met}}{H_{met}}\right)^{\alpha_{met}} \left(\frac{H_{bldg}}{\delta_{bldg}}\right)^{\alpha_{bldg}} \quad (22)$$

Where  $U_{met}$  is the wind speed at measurement point.  $H_{met}$  is the height of measurement point.  $\delta$  is the atmospheric boundary layer thickness.

This method is implemented in the building envelope model.

#### 4. Test with ASHRAE 140 (BESTEST)

ANSI/ASHRAE Standard 140 [3] *Method of Test for the Evaluation of Building Energy Analysis Computer Programs*, sets forth procedures for testing building energy simulation software. ASHRAE Standard 90.1 [4], *Energy Standard for Buildings Except Low-Rise Residential Buildings*, requires that “simulation program shall be tested according to ANSI/ASHRAE Standard 140, and the results shall be furnished by the software provider.”

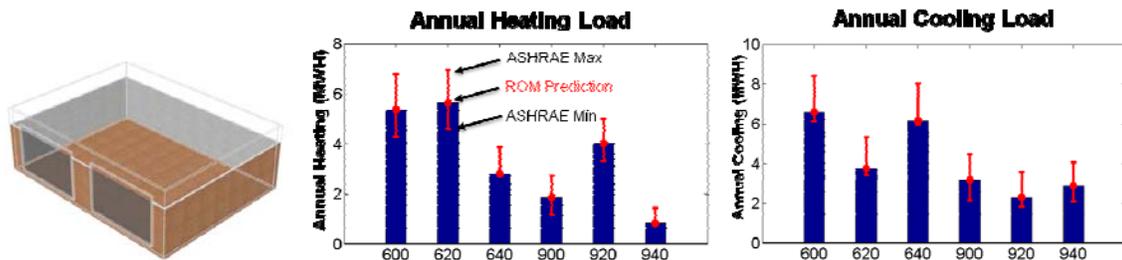


Figure E.5 Results for the ASHRAE BESTEST

Figure E.5 shows the annual load predictions of the ROM thermal network model for various ASHRAE BESTEST cases (numbers are shown on the x-axis), with the bars showing the loads predicted in different cases. For each test case, the ASHRAE Standard provides a range of results produced by reference programs. If test results fall within or close to this range, the subject software is considered to yield acceptable accuracy. Cases 600, 620, 640, 900, 920 and 940 for ROM building envelope model were tested. All predicted loads were in the range of example results from the Standard.

#### References

- [1] ASHRAE. 2009. ASHRAE Fundamentals . ASHRAE.
- [2] Gowri, K., Winiarski, D. and Jarnagin, R. 2009. *Infiltration Modeling Guidelines for Commercial Building Energy Analysis*, PNNL-18898.
- [3] ASHRAE. 2004. ANSI/ASHRAE Standard 140-2004. *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*.
- [4] ASHRAE. 2007. ANSI/ASHRAE/IESNA Standard 90.1-2007. *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

## APPENDIX F: LOAD ESTIMATION

Load Estimation: The load estimation algorithm [1] was adapted for the purpose of estimating the unknown building lumped internal load from the available model and measurements. The internal load herein comprises of plug, occupancy and lighting loads. The system model was augmented with states defining the internal load and driven with white noise (Equation 1). The extended Kalman filter is then employed to estimate the load. Please refer to [1] for more details on the filter.

$$X = \begin{bmatrix} \dot{x} \\ \dot{Q}_{\text{int}} \end{bmatrix} = \begin{bmatrix} f(x, u) + f(x, \theta) + Q_{\text{int}} + w_x \\ w_Q \end{bmatrix} \quad (1)$$

$$Y = C^T x + v$$

**Additional Capabilities/ Flexibilities** provided in this project are:

1. **Constraint Handling:** The EKF implementation was extended to handle time-varying lower and upper bound constraints on the internal load. The algorithm requires the user to specify these bounds a-priori, otherwise a default value of zero lower bound is used to reflect the fact that internal loads (physically) can only be non-negative. The bound specification is required to be a Ndata by Nzones matrix, where Ndata is number of data points and Nzones is the number of zones for which load estimates is required.

Any available information on the internal load can easily be incorporated in to the constraints. For example, if the lighting load is known, the lower bound will be set to a minimum value equal to the lighting load for each zone. Otherwise, the model can be modified to include the known component of the load while the estimator only computes the unknown component. The constrained load estimation is handled with an algorithm that projects the unconstrained estimate unto the user defined constraint surface. Specifically, the projection algorithm presented in ([1], page 13) is implemented for this purpose.

2. **Consolidation of Output Model:** The original KF code requires one function file per output, resulting in unnecessary many function files for large buildings with many zones. Since the output measurements in the buildings is usually the zone temperature. The KF is revised to accept one single function file for all the specified outputs.
3. **Automatic calculation of Jacobian:** EKF requires the calculation of the partial derivative matrices or Jacobian (eqn 2) at the current state estimate.

$$A = \left. \frac{\partial f}{\partial x} \right|_{\hat{x}, \hat{u}} \quad (2)$$

Since the functional form of the model is not available for analytical computation of the Jacobian, it is computed numerically by finite difference. The advantage of this is that

the user only need to provide the building model and the Jacobian is calculated as part of the estimation routine.

**Implementation:** The estimation algorithm is embedded in to an existing model simulation code. The user is expected to interact only with the main file and the input file. The user provides information on the data and system's model in the main file and provides the constraints and the covariance matrices required by the load estimator in the input\_file.

**Simulation Example: Drill Hall - Conference room on the 2nd floor**

The load estimator was validated using data generated from a 3R2C model. Figure F.1 shows the load estimation result, confirming the effectiveness of the estimation tool. Next the estimator was applied to data generated from Energy plus. While the estimator captures the basic behavior of the actual load (Figure F.2), it is obvious that it also accounts for other uncertainties in the model in an attempt to minimize the error between E+ and ROM outputs.

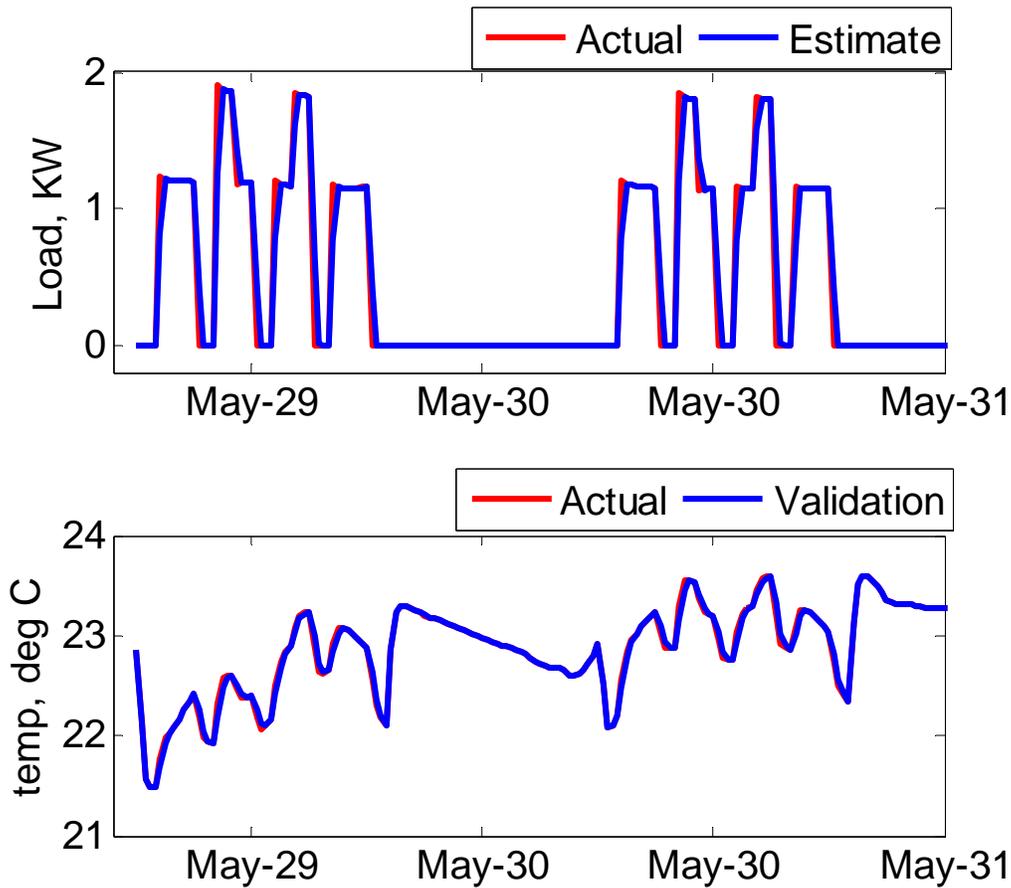


Figure F.1 Validation of Load Estimator

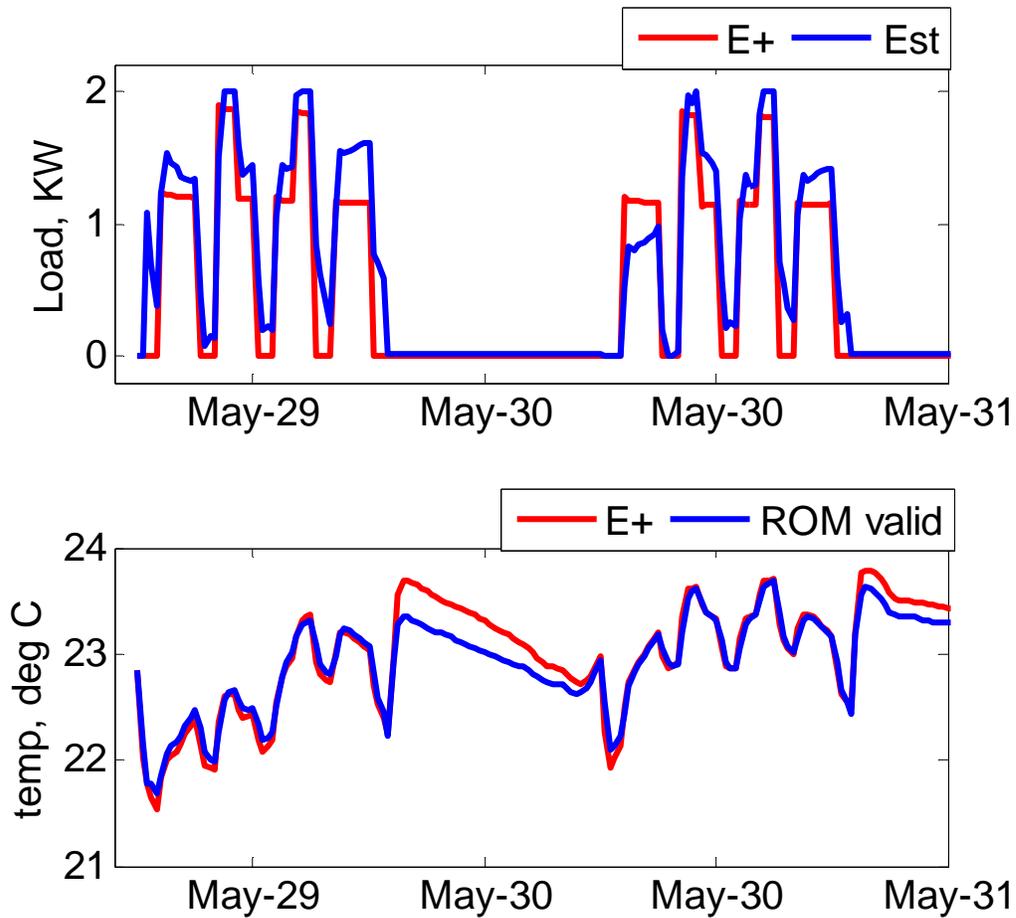


Figure F.2 Constrained Load Estimator Applied to EnergyPlus Data.

Day time maximum load = 2KW; Night time maximum load = 20W.  
 Minimum load for all time = 0W.

**References:**

[1] O'Neill, D., S. Narayanan, and R. Brahme. 2010. Model-based thermal load estimation in buildings, the Fourth National Conference of IBPSA-USA

## APPENDIX G: HVAC EQUIPMENT MODELS

This Appendix describes the HVAC equipment models in details. The current library includes models for the following HVAC equipment:

- Electric chiller
- Absorption chiller
- Cooling tower
- Cooling coil
- Heating coil
- Fan/pump
- Air side economizer
- VAV box

### Electric Chiller

#### Overview

This is for a description of the lumped steady-state model for air- or water-cooled electric chillers based on the EnergyPlus [1] formulation. The model uses performance information at design conditions along with three curve fits for cooling capacity and efficiency to determine chiller operation at off-design conditions.

The correlation based model calculates the thermal performance and the power consumption of the chiller.

This model does not simulate the performance of individual components inside the chiller system. It does not simulate thermal performance or power consumption of associated pumps or cooling towers. Models for such auxiliary equipment are created in separate files.

#### Applicability

Equipment: electric chiller.

Type of model: lumped, steady-state.

Applicable ranges: the applicable range of the correlation-based model is mainly defined by the range of the data used to create the model. As an example, model limits for the Carrier 100-ton air cooled chiller in the Navy Drill Hall are listed in the following table.

Note: range of parameters should not exceed manufacturer's operating envelope.

Table G.1 Applicable Ranges of the Electric Chiller Model

Variable	Unit	Min	Max
Temperature of Air Entering Condenser	°C	14	35
Temperature of Chilled Water Leaving Chiller	°C	5	12
Part Load Ratio	--	0.1	1.2

#### Model Description

Chiller performance curves can be generated by fitting manufacturer's catalog data or measured data. The three curves are defined as follows:

$$CAPFT = a_1 + b_1 \times T_{eo} + c_1 \times T_{eo}^2 + d_1 \times T_{ci} + e_1 \times T_{ci}^2 + f_1 \times T_{eo} \times T_{ci}$$

$$EIRFT = a_2 + b_2 \times T_{eo} + c_2 \times T_{eo}^2 + d_2 \times T_{ci} + e_2 \times T_{ci}^2 + f_2 \times T_{eo} \times T_{ci}$$

$$EIRFPLR = a_3 + b_3 \times PLR + c_3 \times PLR^2, \text{ where } PLR = \frac{Q_e}{Q_{e, \text{available}}(T_{eo}, T_{ci})}$$

where,

PLR: part load ratio;

Teo, Tci: fluid temperatures at outlet of evaporator and inlet of condenser, °C;

CAPFT: cooling capacity factor as function temperatures;

EIRFT, EIRPLR: efficiency factor as functions of temperatures and part load ratio;

a~f: coefficients.

Refer to the EnergyPlus Engineering Reference [1] for more details.

#### Inputs/Outputs/Parameters

Table G.2 Inputs, Outputs and Parameters of the Electric Chiller Model

<b>Inputs (real-time values from system or related components)</b>	
Tcwe	Temperature of water entering chiller from secondary loop (or building) , °C;
Tcwl	Temperature of water leaving chiller from secondary loop (or building) , °C;
Qloadevap	Cooling load on chiller from secondary loop (or building), W;
Tconde	Temperature of fluid entering condenser from weather, °C;
Mdotwevap	Mass flow rate of chilled water from secondary loop (or building), kg/s;
<b>Outputs</b>	
Pchiller	Chiller power consumption, W;
Pcondfan	Chiller condenser fan power consumption, W;
ChillerCOP	Chiller COP rating
<b>Parameters</b>	
<b>Design parameters</b>	
Qref	Chiller rating capacity, W;
COPref	Reference Chiller COP rating;
Mdotwevapref	Mass flow rate of chilled water, kg/s; 224.7 GPM;
Tcwlsp	Setpoint of chilled water temperature leaving chiller, °C;
PLR_minunloadratio	Minimum unload ratio of chiller;
Pcondfanratio	Chiller condenser fan power ratio, W/W;
eff_compmotor	Compressor motor efficiency;
<b>Parameters generated from data</b>	
Chiller capacity function of temperature, ChillerCapFTemp	
cqt(1)	Coefficient1 Constant
cqt(2)	Coefficient2 Tcwl

cqt(3)	Coefficient3 T <sub>cwl</sub> <sup>2</sup>
cqt(4)	Coefficient4 T <sub>conde</sub>
cqt(5)	Coefficient5 T <sub>conde</sub> <sup>2</sup>
cqt(6)	Coefficient6 T <sub>cwl</sub> *T <sub>conde</sub>
Energy input to cooling output ratio function of temperature, ChillerEIRFTemp	
cet(1)	Coefficient1 Constant
cet(2)	Coefficient2 T <sub>cwl</sub>
cet(3)	Coefficient3 T <sub>cwl</sub> <sup>2</sup>
cet(4)	Coefficient4 T <sub>conde</sub>
cet(5)	Coefficient5 T <sub>conde</sub> <sup>2</sup>
cet(5)	Coefficient6 T <sub>cwl</sub> *T <sub>conde</sub>
Energy input to cooling output ratio function of part load ratio, ChillerEIRFPLR	
cep(1)	Coefficient1 Constant
cep(2)	Coefficient2 PLR
cep(3)	Coefficient3 PLR <sup>2</sup>

## Absorption Chiller

### Overview

This is for a description of the lumped steady-state model for steam driven absorption chiller. The model uses performance information at design condition along with two curve fits for cooling capacity and heat input to determine chiller operation at off design conditions.

This model does not simulate the performance of individual components inside the chiller system. It does not simulate thermal performance or power consumption of associated pumps or cooling towers.

### Applicability

Equipment: steam driven absorption chiller

Type of model: lumped, steady-state

Applicable ranges: the applicable range of the correlation-based model is mainly defined by the range of the data used to create the model. As an example, model limits for the Trane ABTF NTON-500 chiller in the Navy Buildings 7113/7114 are listed Table G.3.

Note: range of parameters should not exceed manufacturer's operating envelope.

Table G.3 Applicable Ranges of the Absorption Chiller Model

Variable	Unit	Min	Max
Temperature of Air Entering Condenser	°C	25	31
Temperature of Chilled Water Leaving Chiller	°C	5	12

### Model Description

Chiller performance curves can be generated by fitting manufacturer's catalog data or measured data. The two curves are defined as follows:

$$\text{ChillerCapFTemp} = \text{cqt}(1) + \text{cqt}(2)*\text{Twel} + \text{cqt}(3)*\text{Twel}*\text{Twel} + \text{cqt}(4)*\text{Twce} + \text{cqt}(5)*\text{Twce}*\text{Twce} + \text{cqt}(6)*\text{Twel}*\text{Twce};$$

$$\text{GenHIRFTemp} = \text{cgt}(1) + \text{cgt}(2)*\text{Twel} + \text{cgt}(3)*\text{Twel}*\text{Twel} + \text{cgt}(4)*\text{Twce} + \text{cgt}(5)*\text{Twce}*\text{Twce} + \text{cgt}(6)*\text{Twel}*\text{Twce};$$

where,

Twce: temperature of water entering condenser, °C;

Twel: temperature of water leaving evaporator, °C;

ChillerCapFTemp: cooling capacity ratio (relative to design capacity) as function of Twce and Twel, nd;

GenHIRFTemp: generator heat input ratio (relative to design heat input) as function of Twce and Twel, nd;

cgt, cgt: correlation coefficients generated from data.

The model format was adopted originally from EnergyPlus and was modified later due to issues of data availability and quality from the test building. However, I/O structure is still maintained so that the model can be modified if data available for other formats, e.g., the EnergyPlus model with part load ratio curves.

### Inputs/Outputs/Parameters

Table G. 4 Inputs, Outputs and Parameters of the Absorption Chiller Model

<b>Inputs</b>	
Twce*	Temperature of water entering chiller evaporator from secondary loop (or building) , °C;
Twel	Temperature of water leaving chiller evaporator to secondary loop (or building) , °C;
Twce	Temperature of water entering chiller condenser from weather, °C;
Mdotwe	Mass flow rate of chilled water from secondary loop (or building), kg/s;
Mdotwc	Mass flow rate of cooling water from cooling tower, kg/s;
<b>Outputs</b>	
Qgen	Heat load of generator, W;
Ppump	Pump power input, W;
Qcond	Condenser heat load, W;
Twcl	Temperature of water leaving condenser, °C;
ChillerCOP	COP of chiller;
Mdotwg	Mass flow rate of steam/condensate;
<b>Parameters</b>	
<b>Design Values</b>	
Heatsource	Type of driving force, 1: steam; 2: hot water. (hot water calculation not tested);
Qref	Chiller rating capacity, W; 493 tons for the ABTF500 unit;
Twel_stpt	Setpoint of chilled water temperature leaving chiller, °C

COPref	Rating COP;
Mdotweref	Mass flow rate of chilled water, kg/s;
Ppumpref	Total electric power of pumps in chiller, W;
hfg	Latent heat of vapor, J/kg;
dTsc	Subcooling in generator, default 1 in EnergyPlus max 20, °C;
dTsc_loop	subcooling in loop due to heat loss in EnergyPlus , default 0 in EnergyPlus;
<b>Parameters derived from data</b>	
ChillerCapFTemp	Chiller capacity function of temperature
cqt(1)	Coefficient1 Constant
cqt(2)	Coefficient2 Twel
cqt(3)	Coefficient3 Twel <sup>2</sup>
cqt(4)	Coefficient4 Twce
cqt(5)	Coefficient5 Twce <sup>2</sup>
cqt(6)	Coefficient6 Twel*Twce
cqt(7) *	Coefficient7 Twge
cqt(8) *	Coefficient8 Twge <sup>2</sup>
cqt(9) *	Coefficient9 Twel*Twce*Twge
GenHIRFTemp	Generator heat input ratio function of temperature
cgt(1)	Coefficient1 Constant
cgt(2)	Coefficient2 Twel
cgt(3)	Coefficient3 Twel <sup>2</sup>
cgt(4)	Coefficient4 Twge
cgt(5)	Coefficient5 Twge <sup>2</sup>
cgt(6)	Coefficient6 Twel*Twge
GenHIRFPLR *	Generator heat input ratio function of part load ratio
cgp(1)	Coefficient1 Constant
cgp(2)	Coefficient2 PLR
cgp(3)	Coefficient3 PLR <sup>2</sup>
PumpEIRFPLR *	Solution pump power ratio function of part load ratio
cgp(1)	Coefficient1 Constant
cgp(2)	Coefficient2 PLR
cgp(3)	Coefficient3 PLR <sup>2</sup>
<b>Property Data</b>	
Cpw	Specific heat of water, J/kg. °C

\* Not used in current model due to lack of data.

## Cooling Tower

### Overview

This is a description of the lumped steady-state model of cooling tower with variable speed fans. It is based on empirical curve fits of manufacturer's performance data or field measurements. User specifies tower performance at design conditions, and empirical curves are used to determine the approach temperature and fan power at off-design conditions.

This model does not calculate the detailed heat and mass transfer process of the cooling tower.

### Applicability

Equipment: cooling tower with variable speed fans

Type of model: lumped, steady-state

Applicable ranges: this model is based on the YorkCalc correlation which is applicable to a wider range compared to the CoolTool formula. Applicable ranges of the model are listed in Table G.5.

Note: ranges of parameters should not exceed manufacturer's operating envelope.

Table G. 5 Applicable Ranges of the Cooling Tower Model

<b>Variables</b>	<b>Limits</b>
minimum inlet air wet-bulb temperature (°C)	-34.4
maximum inlet air wet-bulb temperature (°C)	26.7
minimum tower range temperature (°C)	1.1
maximum tower range temperature (°C)	22.2
minimum tower approach temperature (°C)	1.1
maximum tower approach temperature (°C)	40
minimum water flow rate ratio	0.75
maximum water flow rate ratio	1.25
maximum liquid-to-gas ratio	8

### Model Description

The variable speed tower model utilizes user-defined tower performance at design conditions along with empirical curves to determine tower heat rejection and fan power at off-design conditions. Makeup water usage is also modeled based on user inputs, tower entering air conditions, and tower operation. The following section describes the main equation for approach temperature calculation.

Heat rejection is modeled based on the YorkCalc correlation, which calculates the tower approach temperature using a polynomial curve fit with 27 terms and four independent variables.

$$\begin{aligned}dT_{app} = & capp(1) + capp(2)*Tawbe + capp(3)*Tawbe^2 + capp(4)*dT_w + \\ & capp(5)*Tawbe*dT_w + capp(6)*Tawbe^2*dT_w + capp(7)*dT_w^2 + \\ & capp(8)*Tawbe*dT_w^2 + capp(9)*Tawbe^2*dT_w^2 + capp(10)*ffwa +\end{aligned}$$

$$\begin{aligned}
& \text{capp}(11)*\text{Tawbe}*\text{ffwa} + \text{capp}(12)*\text{Tawbe}^2*\text{ffwa} + \\
& \quad \text{capp}(13)*\text{dT}w*\text{ffwa} + \text{capp}(14)*\text{Tawbe}*\text{dT}w*\text{ffwa} + \\
& \quad \text{capp}(15)*\text{Tawbe}^2*\text{dT}w*\text{ffwa} + \\
& \text{capp}(16)*\text{dT}w^2*\text{ffwa} + \text{capp}(17)*\text{Tawbe}*\text{dT}w^2*\text{ffwa} + \\
& \text{capp}(18)*\text{Tawbe}^2*\text{dT}w^2*\text{ffwa} + \text{capp}(19)*\text{ffwa}^2 + \\
& \text{capp}(20)*\text{Tawbe}*\text{ffwa}^2 + \text{capp}(21)*\text{Tawbe}^2*\text{ffwa}^2 + \\
& \text{capp}(22)*\text{dT}w*\text{ffwa}^2 + \text{capp}(23)*\text{Tawbe}*\text{dT}w*\text{ffwa}^2 + \\
& \text{capp}(24)*\text{Tawbe}^2*\text{dT}w*\text{ffwa}^2 + \text{capp}(25)*\text{dT}w^2*\text{ffwa}^2 + \\
& \text{capp}(26)*\text{Tawbe}*\text{dT}w^2*\text{ffwa}^2 + \text{capp}(27)*\text{Tawbe}^2*\text{dT}w^2*\text{ffwa}^2;
\end{aligned}$$

where:

dTapp: approach temperature (°C) = outlet water temperature - inlet air wet-bulb temperature;

dTw: range temperature (°C) = inlet water temperature - outlet water temperature;

Tawbe: inlet air wet-bulb temperature (°C);

Ffwa: liquid-to-gas ratio = ratio of water flow rate ratio (FRwater) to air flow rate ratio (FRair);

Capp(i): correlation coefficients;

FRair = air flow rate ratio (actual air flow rate divided by design air flow rate);

FRwater = water flow rate ratio (actual water flow rate divided by design water flow rate).

For more details, refer to the EnergyPlus Engineering Reference [1].

### Inputs/Outputs/Parameters

Table G. 6 Inputs, Outputs and Parameters of the Cooling Tower Model

<b>Inputs</b>	
Tadbe	Entering air dry bulb temperature, °C;
RHae	Entering air relative humidity, 0-1;
Twe	Entering water temperature, °C;
Vdotw	Water volume flow rate, m <sup>3</sup> /s.
<b>Outputs</b>	
Twl	Leaving water temperature, °C;
Pow_ct	Cooling tower power input, W;
Vdotw_makeup	Makeup water volume flow rate, m <sup>3</sup> /s;
Vdota	Air flow rate, m <sup>3</sup> /s;
<b>Parameters</b>	
ncell	Number of cells;
Twl_stpt	Setpoint of leaving water temperature, °C;
Vdota_des	Design value of air volume flow rate, m <sup>3</sup> /s;
Vdotw_ref	Reference value of water volume flow rate, m <sup>3</sup> /s;
fcfc	Fraction of cooling tower capacity in free convection at zero fan speed vs. max fan speed, nd;
capp	Coefficients for approach temperature (Tapp) calculation, nd;
cpf	Coefficients for fan power vs. air volume flow rate;
Tawbe_min	Minimum inlet air wet-bulb temperature, °C;
Tawbe_max	Maximum inlet air wet-bulb temperature, °C;

dTw_min	Minimum tower range temperature, °C;
dTw_max	Maximum tower range temperature, °C;
dTapp_min	Maximum tower approach temperature, °C;
dTapp_max	Maximum tower approach temperature, °C;
fw_min	Maximum water flow rate ratio, nd;
fw_max	Maximum water flow rate ratio, nd;
ffwa_min	Maximum liquid-to-gas ratio, nd;
fa_min	Maximum air flow rate ratio, nd;
fa_max	Maximum air flow rate ratio, nd;
makeup_evap	Option of calculation of makeup water due to evaporation. 1: assume saturated leaving air, 2. use loss factor fw_evap, nd;
fw_evap	Loss factor of water due to evaporation, percent of condenser water flow rate per degree change of water temperature, 0.15-0.27, percent/K;
fw_drift	Loss factor of water due to drift, percent of design water flow rate lost to drift at the tower design air flow rate, percent;
fscon	Ratio of solids in the blowdown water to solids in the makeup water, 3-5, nd;
itmax	Maximum number of iterations;
Cpw	Specific heat of water entering chiller, J/kg.°C;
Patm	Atmospheric pressure, Pa.

## Cooling Coil

### Overview

This is a description of the lumped steady-state model for air-water cooling coil. The model calculates leaving air and water conditions based on the UA value derived from design schedule and calibrated with measured data available.

This model does not calculate the detailed heat transfer process due to the constraint of data availability in practice.

### Applicability

Equipment: air-water cooling coil

Type of model: lumped, steady-state

Applicable ranges: the ranges depend on the bounds of data available for the validated UA. As an example, applicable ranges of the Navy Drill Hall building are listed in the following table.

Note: range of parameters should not exceed manufacturer's operating envelope.

Table G. 7 Applicable Ranges of the Air-Water Cooling Coil Model

Variable	Unit	Min	Max
Temperature of Air Entering Coil	°C	18	30
Relative Humidity of Air Entering Coil	%	20	100
Mass Flow Rate of Air	kg/s	8.3	9.1

Temperature of Water Entering Coil	°C	5.1	12.2
Mass Flow Rate of Water	kg/s	2.3	9.5

### Model Description

Adopted from the EnergyPlus format, the cooling coil model is based on approach to the saturation line in the heat and mass transfer process. As an equivalent psychrometric calculation, UA values are derived from the bypass factor and effectiveness-NTU method using temperature for dry coil and enthalpy for wet coil conditions.

$$UA_t = e_{NTU}(m_{dot{a}}, h_{a_i}, m_{dot{w}} * c_{pw} / c_{psat}, h_{a_{Twi}})$$

$$UA_o = -\log(BPh) * m_{dot{a}} * c_{pa}; UA_i = c_{psat} / (1/UA_h - c_{pa}/UA_o)$$

where,

UA<sub>t</sub>, UA<sub>o</sub>, UA<sub>i</sub>: UA values for total, external and internal heat transfer rate, W/K;

M<sub>dot{a}</sub>, M<sub>dot{w}</sub>: air and water mass flow rate, kg/s;

c<sub>pa</sub>, c<sub>pw</sub>, c<sub>psat</sub>: specific heat of air, water and air at equivalent saturation condition, J/(kg.K);

BPh: bypass factor, nd.

For the cooling coil model, eight functions for coil and 15 psychrometric functions have been created in Matlab. For more details, refer to the EnergyPlus Engineering Reference [1].

### Inputs/Outputs/Parameters

Table G. 8 Inputs, Outputs and Parameters of the Air-Water Cooling Coil Model

<b>Inputs</b>	
InletWaterMassFlowRate	Mass flow rate of water, kg/s
InletWaterTemp	Temperature of water entering coil, °C
InletAirMassFlowRate	Mass flow rate of air, kg/s
InletAirTemp	Temperature of air entering coil, °C
InletAirHumRat	Humidity ratio of air entering coil, °C
<b>Outputs</b>	
OutletWaterTemp	Temperature of water leaving coil, °C
OutletAirTemp	Temperature of air leaving coil, °C
OutletAirHumRat	Humidity ratio of air leaving coil, °C
<b>Parameters</b>	
UACoilTotal	Total heat transfer rate, W/K
UACoilInternal	Internal heat transfer rate, W/K
UACoilExternal	External heat transfer rate, W/K

## Heating Coil

### Overview

This is a description of the model of air-water heating coil. The model calculates leaving air and water temperatures based on the UA value derived from design schedule and calibrated if measured data is available.

This model does not calculate the detailed heat transfer process due to the constraint of data availability in practice.

### Applicability

Equipment: air-water heating coil

Type of model: lumped, steady-state

Applicable ranges: the ranges depend on the bounds of data used for validation of the model (not available in this study).

### Model Description

The air-water heating coil model uses performance information at design conditions to calculate the design UA value. If measured data is available, UA value should be calibrated and coil performance should be validated especially for off-design conditions.

The heating coil model is based on the effectiveness-NTU method for cross flow with the derived UA as well as temperature and flow rate of entering air and water, which is similar to the dry-coil condition of the cooling coil model.

For more details, refer to the EnergyPlus Engineering Reference [1].

### Inputs/Outputs/Parameters

Table G. 9 Inputs, Outputs and Parameters of the Air-Water Heating Coil Model

<b>Inputs</b>	
AirMassFlow	Air mass flow rate, kg/s
WaterMassFlowRate	Water mass flow rate, kg/s
TempAirIn	Entering air temperature, °C
TempWaterIn	Entering water temperature, °C
<b>Outputs</b>	
TempAirOut , C	Leaving air temperature, °C
TempWaterOut	Leaving water temperature, °C
<b>Parameters</b>	
UA	Heat transfer rate, W/C
Cpw	Specific heat of water, J/(kg. °C)

## Fan/Pump

### Overview

This is a description of the model of variable speed fans and pumps. The model uses measured data of air/water flow rate or fan/pump speed to calculate power input of the fan or pump. Coefficients for the correlation are derived from test data under normal operating conditions. The fan/pump power model can be used in energy prediction and monitoring of fan/pump status.

This model is not based on fan curves from manufacturers to avoid inaccuracy in power prediction due to the variations in field application from lab test conditions of manufacturers.

### Applicability

Equipment: variable speed fan/pump

Type of model: lumped, steady-state

Applicable ranges: the ranges are defined by the data used to generate the correlation coefficients. As an example, applicable ranges of models for VFD fans/pumps in buildings 7113/7114 are listed in following table.

Table G. 10 Applicable Ranges of the Variable Speed Fan/Pump Model

Unit	Min. speed (%)	Max. speed (%)
b7113_ah1raf	55	65
b7113_ah1saf	55	100
b7113_ah2raf	55	92
b7113_ah2saf	55	100
b7113_ah3raf	50	100
b7113_ah3saf	37	45
b7113_ah4raf	999	999
b7113_ah4saf	55	88
b7113_te1	44	92
b7113_te2	37	90
b7113_te4	100	100
b7114_ah1raf	60	94
b7114_ah1saf	57	98
b7114_ah2raf	57	100
b7114_ah2saf	40	100
b7114_ah3raf	50	100
b7114_ah3saf	91	100
b7114_ah4raf	65	100
b7114_ah4saf	65	88
b7114_chsp4	49	100
b7114_chsp5	53	97
b7114_chsp6	49	100
b7114_ctr1	40	60

b7114_ctr2	17	40
b7114_ctr3	18	40
b7114_hxp8	48	66
b7114_hxp9	45	70
b7114_hxp10	54	100
b7114_te1	41	59
b7114_te2	36	41
b7114_te4	100	100

### Model Description

The fan/pump power model can be created as a function of either volumetric flow rate of air/water or fan/pump speed signal, depending on availability of data.

$$\text{Fan power} = c0 + c1*x + c2*x^2 \quad (\text{Watts})$$

where,

c0-c2: coefficients created from data;

x: air/water flow rate (m<sup>3</sup>/s) or fan/pump speed signal (%).

### Inputs/Outputs/Parameters

Table G.11 Inputs, Outputs and Parameters of the Variable Speed Fan/Pump Model

<b>Inputs</b>	
csf	Fan speed control signal, 0-100
tai	Air temperature at inlet, °C
vdota	Volumetric flow rate of air, m <sup>3</sup> /s
<b>Outputs</b>	
pow	Power input, W
tao	Air temperature at outlet, °C
<b>Parameters</b>	
cpa	Air specific heat, w/kg-°C
cpow	Coefficients of fan power input (W) vs fan speed signal
fh2a	Fraction of fan heat into air
roua	Air density, kg/m <sup>3</sup>
x_min	Minimum speed control signal, 0-100
x_max	Maximum speed control signal, 0-100

## **Economizer**

### Overview

This is a description of the model of temperature or enthalpy differential based economizer control in air handling unit. The air flow rate modulates in cooling mode and stays at minimum in heating mode.

This model does not include dynamic control of damper position in the economizer. The output of this model in cooling mode is fraction of air flow rate relative to the total supply air flow rate, not the damper position.

Applicability

Equipment: air-side economizer

Type of model: lumped, steady-state

Applicable ranges: the ranges depend on the bounds of data defined in field application.

Model Description

The model calculates fraction of outdoor air flow rate relative to the total supply air flow rate based on the differential enthalpy or temperature values among outdoor air, return air and supply air setpoint.

$$\text{Outdoor air fraction} = \frac{(\text{outdoor air temperature/enthalpy} - \text{supply air temperature/enthalpy})}{(\text{return air temperature/enthalpy} - \text{supply air temperature/enthalpy})}$$

Inputs/Outputs/Parameters

Table G. 12 Inputs, Outputs and Parameters of the Economizer Model

<b>Inputs</b>	
T <sub>o</sub>	Outdoor air temperature, °C
RH <sub>o</sub>	Outdoor air relative humidity, nd, 0-1
T <sub>r</sub>	Return air temperature, °C
RH <sub>r</sub>	Return air relative humidity, nd, 0-1
daytype	Wekday(wd) or weekend (we)
timeofday	Current hour of the day, hr
<b>Outputs</b>	
f <sub>Mdot_o</sub>	Fraction of outside air, nd
<b>Parameters</b>	
T <sub>s_stpt_c</sub>	Supply air temperature setpoint in cooling, °C
T <sub>s_stpt_h</sub>	Supply air temperature setpoint in heating, °C
RH <sub>s_stpt_c</sub>	Supply air relative humidity setpoint in cooling, nd, 0-1
V <sub>dot_o_min</sub>	Minimum fluid volume flow rate, m3/s
V <sub>dot_o_max</sub>	Maximum fluid volume flow rate, m3/s
T <sub>o_min</sub>	Minimum outdoor air temperature for economizer operation, °C
T <sub>o_max</sub>	Maximum outdoor air temperature for economizer operation, °C
f <sub>sch_wd_eco</sub>	Schedule factor of economizer during weekdays, nd
f <sub>sch_wd_eco</sub>	Schedule factor of economizer during weekends of holidays, nd

## VAV

### Overview

This is a description of the model of variable air volume box with reheat. It calculates air flow rate as a fraction of the design value in cooling mode and leaving air temperature with minimum air flow rate in heating mode.

This model does not include dynamic control of damper position in the VAV box. The output of this model in cooling mode is fraction of air flow rate relative to design value, not the damper position.

### Applicability

Equipment: VAV box with reheat

Type of model: lumped, steady-state

Applicable ranges: the ranges depend on the bounds of data defined in field application. As an example, applicable ranges of the Navy Drill Hall building are listed in Table G. 13.

Note: Values listed here are from the design schedule. These values should be modified based on field implementation. In some of the VAV boxes in the Navy Drill Hall, the lower limit varied especially in heating mode.

Table G. 13 Applicable Ranges of the VAV Model

	Min. Air Flow Rate (m <sup>3</sup> /s)	Max. Air Flow Rate (m <sup>3</sup> /s)
VAV1	0.153	0.519
VAV2	0.153	0.576
VAV3	0.109	0.441
VAV4	0.212	0.857
VAV5	0.038	0.175
VAV6	0.212	0.897
VAV7	0.153	0.656
VAV8	0.021	0.047

### Model Description

The type of air flow management is based on the logics implemented in the Navy Drill Hall and buildings 7113/7114. In cooling mode, the model calculates the air flow rate as a fraction the design value to maintain the zone temperature. In heating mode, the model calculates water flow rate and leaving air and water temperatures. UA value is derived from design condition and can be tuned if data available.

## Inputs/Outputs/Parameters

Table G. 14 Inputs, Outputs and Parameters of the VAV Model

<b>Inputs</b>	
Ta <sub>i</sub>	Air temperature at inlet of VAV box, °C
Ta <sub>z</sub>	Zone air temperature, °C
Tw <sub>i</sub>	Temperature of water at inlet of reheater, °C
Q <sub>z</sub>	Zone thermal load, W
daytype	Type of day, weekday (1) or weekend/holiday (0)
timeofday	Current hour of the day, 1-24
mode	Zone demand mode, cooling (-1), heating (1) or none (0)
<b>Outputs</b>	
Ta <sub>o</sub>	Air temperature at outlet of VAV box, °C
Mdot <sub>a</sub>	Mass flow rate of supply air, kg/s
Tw <sub>o</sub>	Water temperature at outlet of reheat, °C
Mdot <sub>w</sub>	Mass flow rate of water for reheat, kg/s
Q	Heating demand on reheat, W
f <sub>Mdot</sub>	
<b>Parameters</b>	
<b>Design Parameters</b>	
Mdot <sub>a</sub> max	Design air mass flow rate, kg/s
f <sub>Mdot<sub>a</sub> min</sub>	Minimum air mass flow rate as fraction of design air mass flow rate, nd
UA <sub>des</sub>	Design UA of reheat in VAV box, J/°C
<b>Other Parameters</b>	
f <sub>sch<sub>wd</sub>eco</sub>	Schedule factor of economizer during weekdays, nd
f <sub>sch<sub>wd</sub>eco</sub>	Schedule factor of economizer during weekends of holidays, nd

## References

- [1]. EnergyPlus Engineering Reference. October 2, 2009.  
<http://apps1.eere.energy.gov/buildings/energyplus/>

## APPENDIX H: BUILDING VISUALIZATIONS AND FDD

In this Appendix, the visualization and FDD modules, which have been implemented and demonstrated at Naval Station Great Lakes, are described.

### Architecture and Data Management

Fault Detection/Diagnosis (FDD) and Visualization were implemented as two separate modules. The Fault Detection/Diagnosis module runs in an automated fashion once every four hours for Building 7113/7114. In each instance, it reads the BMS data for the past four hours from the database, performs computations (based on trained diagnostic models), and archives the results back in the database.

The visualization module was implemented as a stand-alone module and was initiated by the user. The user selects the time period that he/she wishes to explore after which the module reads corresponding data from the database and displays them to the user. The FDD/visualization modules have been implemented in MATLAB [1] and interact with the database using MATLAB's database toolbox. Schematics of both the modules are shown in Figure H.1 below.

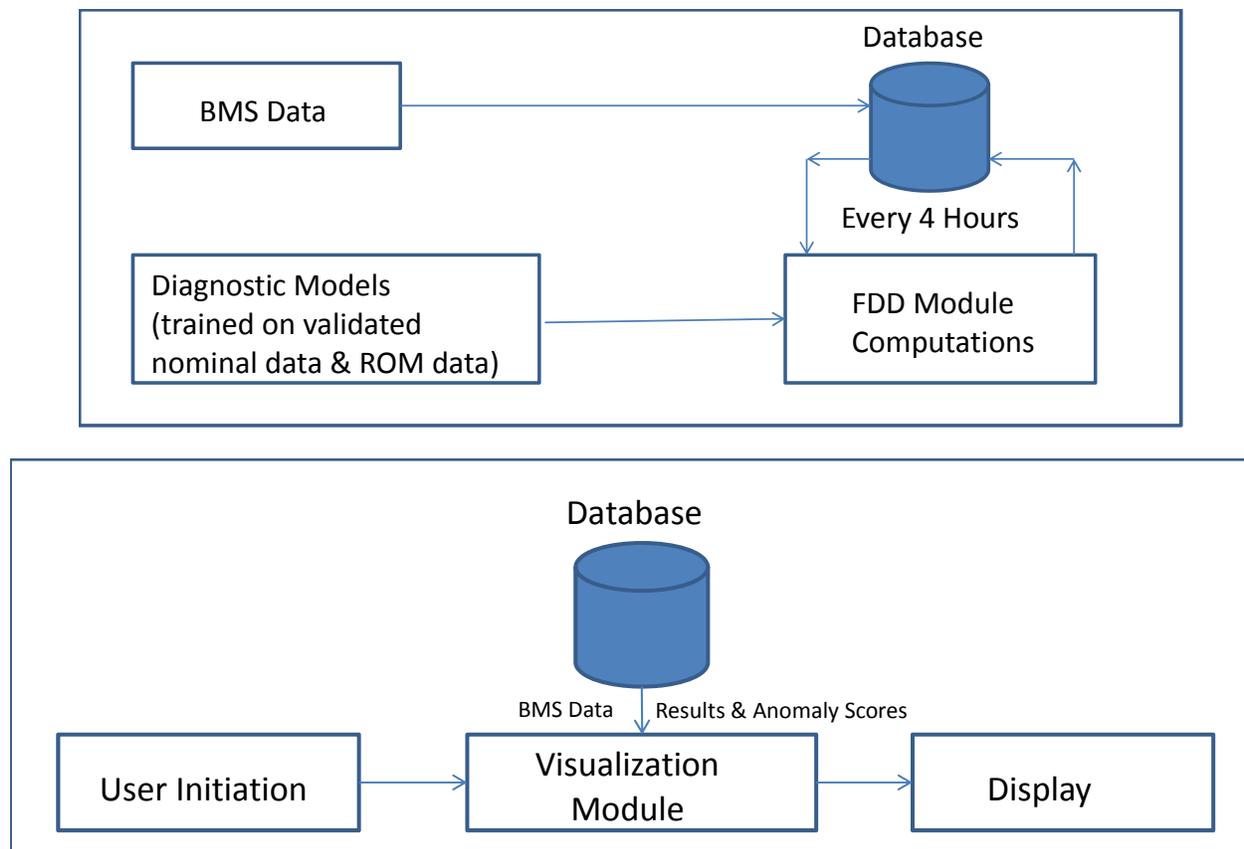


Figure H.1 Schematics for FDD Module and Visualization Module

### *Setup and Commissioning in a New Building*

The following are the steps involved in commissioning the Fault Detection/Diagnosis and Visualization modules.

- 1) Begin archiving BMS data.
- 2) Identify a period of data at least two weeks long and validate for nominal operation. If such data is unavailable or difficult to obtain, utilize the validated reduced-order models to train the diagnostic models (Bayesian Networks).
- 3) Run the initialization code for FDD computations after at least 30 days of data has been accumulated. This sets up all the necessary files for continuous running of the FDD module.
- 4) Use the FDD visualization module after the initialization is complete
- 5) Run the FDD computations module periodically, updating results every four hours, based on new incoming data.

### **Fault Detection and Diagnostics Approach**

The FDD module utilizes data from the BMS as well as simulation outputs from reduced-order models for training. The module primarily uses algorithms from the statistical machine learning literature to characterize the joint probability distributions of data for the purpose of fault detection and fault identification.

The statistical machine learning methods used rely on the assumption that the characteristics of the data variations are relatively unchanged unless a fault occurs in the system. This implies that statistical properties like the mean and variance, at a particular operating point are repeatable, even though the individual values may show significant fluctuations. This repeatability allows thresholds for certain measures that indicate anomalous operation to be determined automatically. This is the essence of the underlying principle used in the FDD module. A class of techniques commonly known as “Probabilistic Graphical Models” was used to characterize the probability distributions of data and we briefly summarize it below.

#### *Probabilistic Graphical Models Overview*

Probabilistic graphical models are a class of models that can represent the joint multivariate probability distribution of a set of random variables. Modeling the joint probability distribution allows one to assign probability values to measured data points and this can be used to detect anomalous events. Any data-point with a low probability assignment can be interpreted as an anomaly.

Probabilistic graphical models provide a compact representation of the joint probability distribution by representing the random variables and the relationships between them as a graphical network. Random variables are represented as nodes in the graph and arcs between nodes represent statistical relationships. In this project, directed arcs were used to represent the relationships. Representing the joint probability distribution as a directed graphical network simplifies the computation of the joint distribution by expressing it as a product of the

conditional probability distributions at every node. The parameters of such models are the conditional distributions at every node.

The advantages of using models as described above can be illustrated using a synthetic example. Considering a scenario where the problem is to model the dependency between the weather (cloudy conditions and rain) and condition of the lawn (sprinkler system and whether the lawn has been watered). Figure H.2 below shows a graphical network corresponding to this problem along with the probability distributions at every node. In the probability tables, T and F represent “True” and “False” respectively. The nodes “Cloudy,” “Sprinkler,” “Rain” and “WetGrass” are represented by their initial letters.

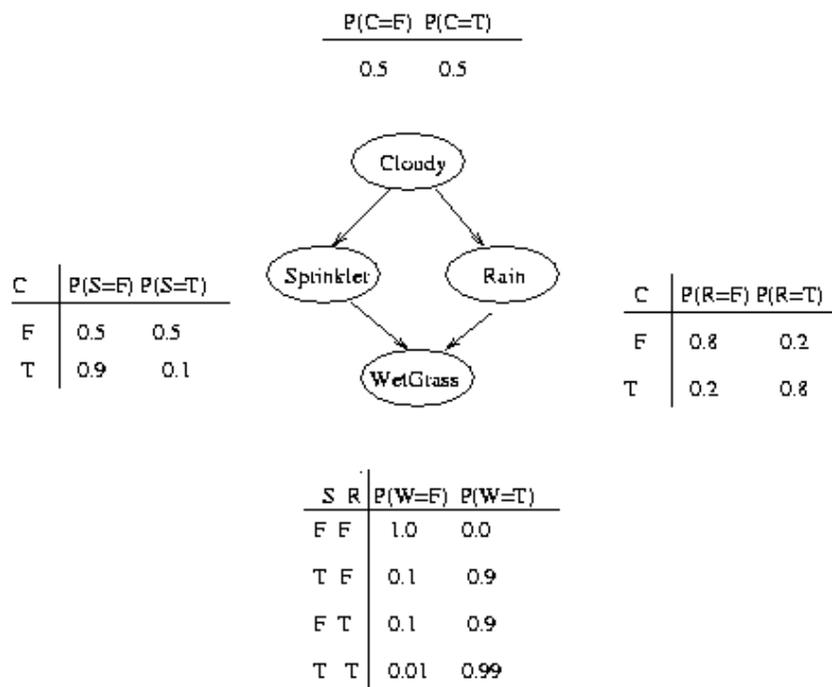


Figure H.2 Graphical Network Example

Given a graphical network like the one shown in Figure H.3, along with the associated conditional probability parameters, one can revise the values of probabilities in light of actual observations. This process is usually referred to as “inference.”

For example, one can engage in “bottom-up” or “diagnostic” reasoning where the problem is to infer the most likely cause given some evidence (i.e. observed data). In the case of the weather and lawn example, if the grass was observed to be wet, one can compute the probabilities that the cause was rain or sprinkler to be 0.708 and 0.43 respectively. The computations result from an application of Bayes’ rule. In this case, it is more likely that the grass was wet due to rain.

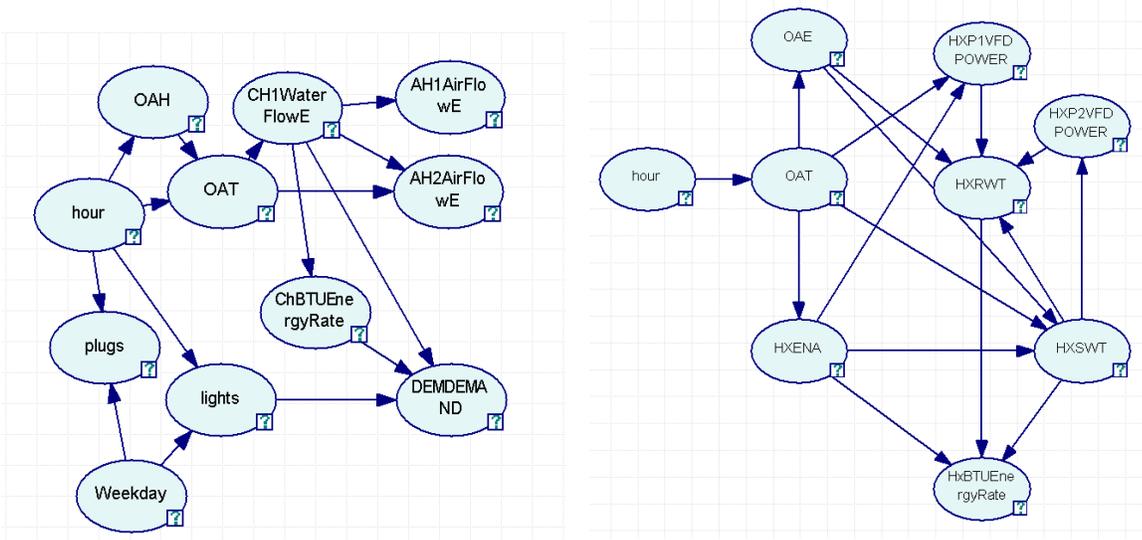
One can also try to understand how causes generate effects via “top-down” or “causal” reasoning. One could answer questions such as specifying the probability that the grass will be wet if it is cloudy. One can also “explain away” observations by updating probabilities when additional “evidence” or observations become available. For example, if the grass was wet and in

addition it was observed that it was raining, one can update the probability that the sprinkler was on and find it to be very low given the new evidence.

In the above toy example, the graphical network was given to us along with the parameters. In real-life problems, this is not available and there are algorithms that help “learn” the structure of the network and the parameters from raw data. One can also use the knowledge of experts in developing the structure of the network or guiding the algorithm to find the right structure.

Given the properties described above and the flexibility of the methods, probabilistic graphical models were used to characterize the data from buildings to detect anomalies.

Since buildings consist of many integrated systems, a whole building graphical network model maybe too complex for tractability. A hierarchical approach is proposed and FDD is done in a top-down manner. At the building level, a system level network models and tracks various systems and interactions between them. Each node in this top-level network leads down to component level FDD modules. In this manner, the size and the complexity of the network, that needs to be dealt with at any point in time, can be kept to a manageable size. For example, the system level graphical network and one of its component networks for Building 7230 are shown in Figure H.3.



*System level graphical network*

*Component level heat exchanger graphical network*

**Figure H.3 Graphical Network for Building 7230**

The graphical structure is learned in a completely data-driven manner to discover the relationships between variables inherent in the data. . The goal of this step is to learn the nominal behavior of the system. If available, measured data was used for training after it has been validated that there were no faults present during the selected time-period. When such data is not available, data from reduced-order models were used to learn the relationships corresponding to nominal behavior. After this step the learned graphical structure is validated against domain knowledge and physics based understanding of the system. At this step several spurious

connections may be removed and some critical ones enforced, the graphical structure is also pruned to keep only necessary variables for dimensionality reduction. At this point the graphical network model for FDD is used to analyze new data to generate an anomaly score quantifying the extent of departure from the nominal performance of variable, given the measurement of other related variables. Based on the anomaly scores and a suitably chosen threshold, faults are detected & diagnosed by identifying anomalous variables in the given set of nodes in the network.

### User Interface and Visualizations

A platform-independent, MATLAB [1] based visualization tool for monitoring building energy consumption, overall building health and integrated building diagnostics has been developed for Building 7114. The Integrated Buildings Energy and Diagnostics (iBED Viz) tool provides an intuitive interface to view energy utilization at the building level and for major components, i.e., lighting, plug loads, heating, cooling, fans and pumps. Advanced visualization features for easy navigation and drill-down analysis have also been implemented. The diagnostics interface takes a top-down approach which allows the operator to see building level health performance as well as component level health performance using a hierarchical building interface that lists key system components such as the chiller, heat exchanger and air handling units (AHU). Key features of the iBED Viz visualization system (highlighted in Figure H.4) are discussed below.

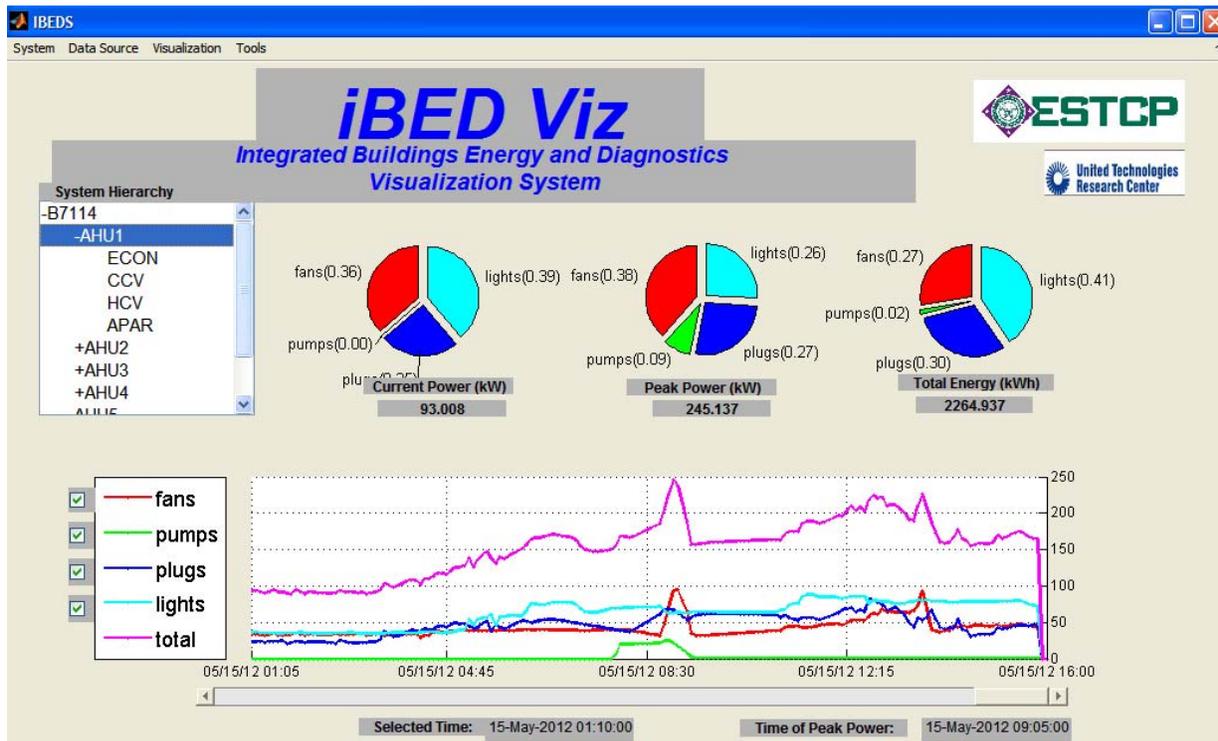


Figure H.4 Overview of the Energy Visualization

### Building Hierarchy

The visualization interface is customizable in that it can load any building hierarchy and customize the display for that building structure. This hierarchical structure allows the user to navigate to different levels of detail while analyzing faults and their origin. Figure H.5 shows the building structure for Building 7114 which is used to navigate through the system. It includes four AHUs a heat exchanger and a chiller. Also, the AHU labels in the system hierarchy are expandable to show components within the AHU – the economizer (ECON), cooling coil valve (CCV) and the heating coil valve (HCV). See Figure H.5 below for an illustration.

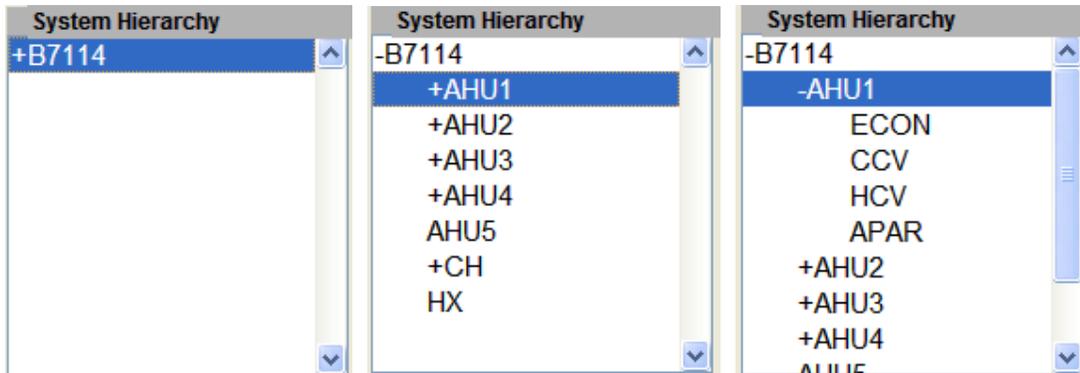


Figure H.5 Building Hierarchy Interface

#### Time-Series Energy Flows

The visualization gives the operator a snap-shot of the system level energy consumption as well as its breakdown into multiple components such as lights and plugs etc. as continuously-updated time series data. The user can thus infer information about how the building is spending energy at different levels of detail by selectively checking the energy modes (fans, pumps, plugs, lights) he/she wishes to visualize, as illustrated in Figure H.6.

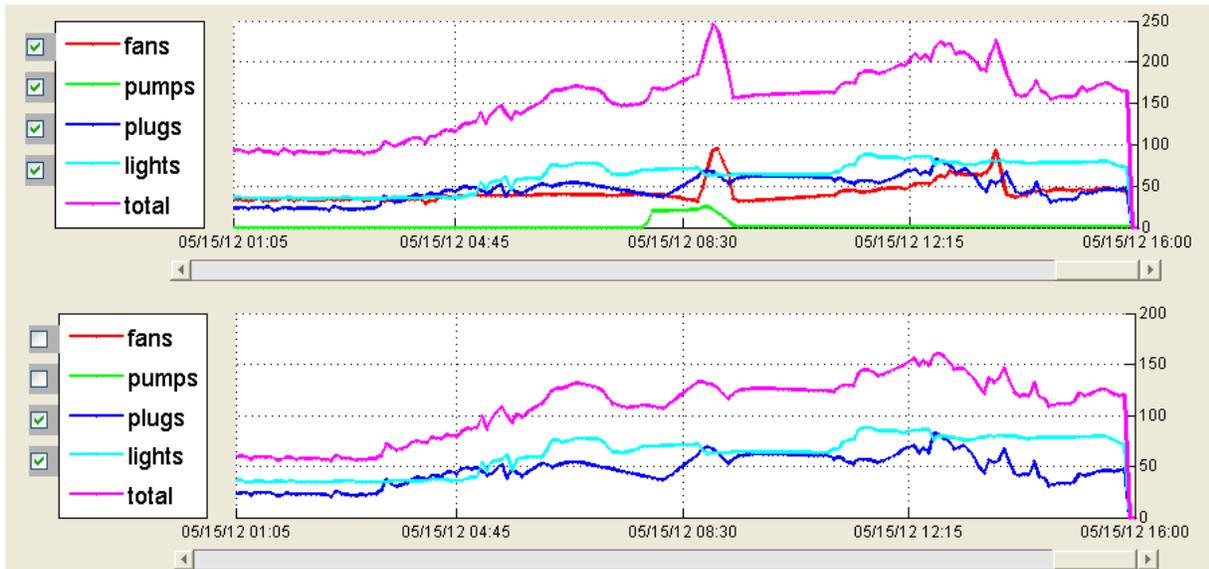


Figure H.6 Time-Series Energy Flows Interface

### Vital Energy Statistics

In addition to the spatial information, cumulative statistics of the energy consumption are calculated and displayed as pie charts as shown in Figure H.7. Currently, these pie charts display cumulative energy consumption, peak energy consumption and instantaneous energy consumption relative to the time-window of display. The instantaneous consumption is calculated based on the first time-sample in the field of view or is based on an operator-selected point in the time-series plot.

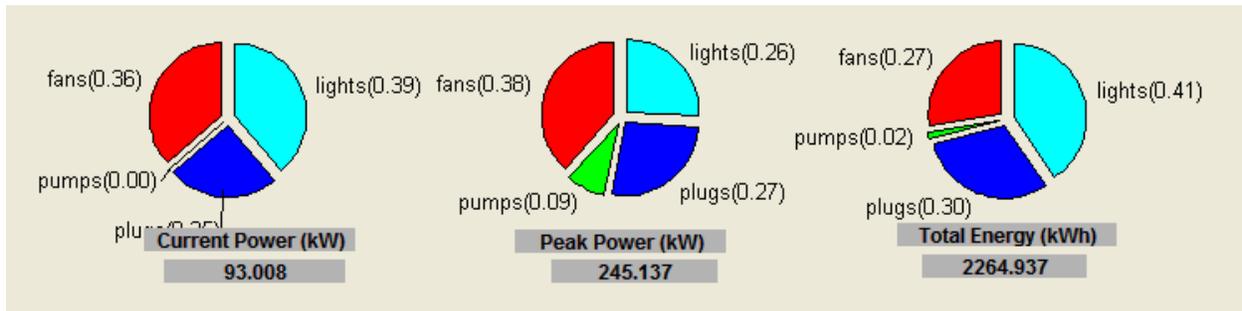


Figure H.7 Energy Statistics Pie Chart Interface

### Panning and Zooming options

The visualization interface gives the operator scrolling and zooming capabilities for better navigating the energy time-series plots.

### Date Range Selection

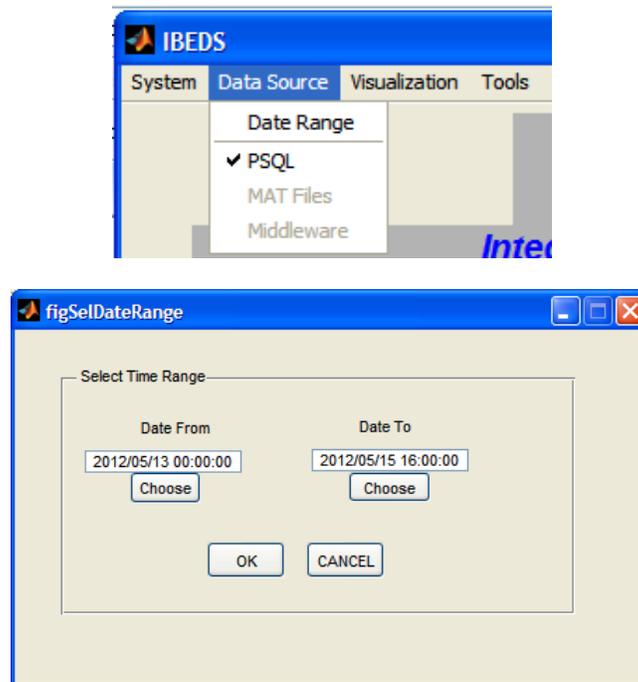


Figure H.8 Data Range Selection Interface

The interface gives the user an option to choose a date range of his/her choice as shown in Figure H.8.

### *Thermal Energy Consumption*

In addition to the electrical energies, the user also has the ability to visualize chilled water or hot water energy consumption by accessing the “visualization” tab from the toolbar. Figure H.9 below is a screenshot of chilled water energy consumption visualization.

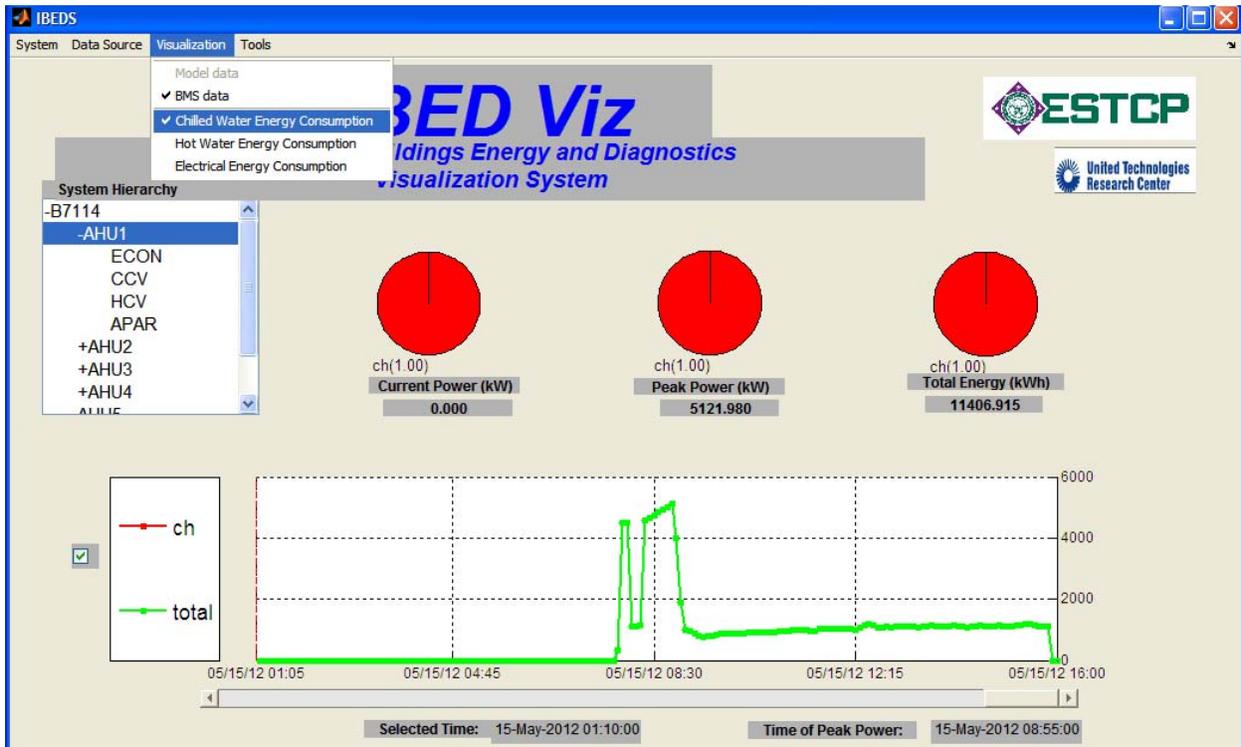


Figure H.9 Chilled Water Energy Consumption Interface

### *NIST APAR Rules for AHUs*

The tool also implements NIST AHU Performance Assessment Rules (APAR) for AHU diagnostics [2]. APAR diagnostics has been implemented as a separate tool and can be accessed by clicking APAR under the AHU of interest in the building hierarchy. Figure H.10 illustrates the building hierarchical pane from the main iBED Viz tool window where user can access APAR rules tool.

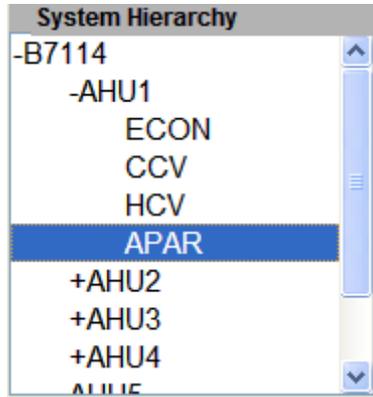


Figure H.10 APAR Rules Tool Interface.

The tool opens in a new window as shown in Figure H.11.

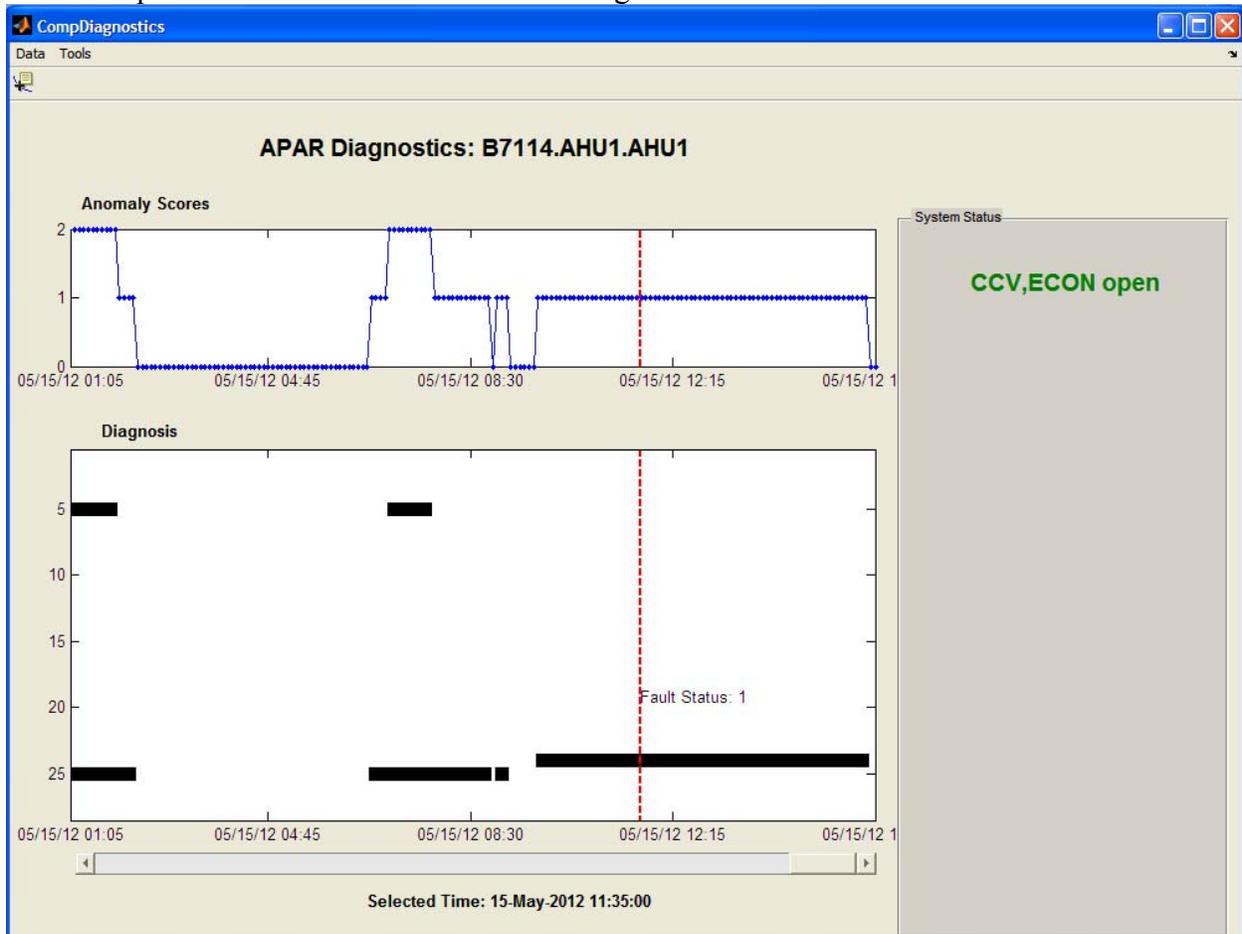


Figure H.11 Overview of the AHU APAR Rules Tool

The top panel in Figure H.11 shows an anomaly score which indicates the number of rules that were fired. The bottom panel shows particular rules that were fired. Each of the 28 rows corresponds to a particular APAR rule. When a particular time is chosen, the rules that fired at the time are displayed in the system status panel on the right. The tool also calculates the energy

impact of the individual rules. The energy impacts can be accessed from the “Tools” menu as shown below in Figure H.12.

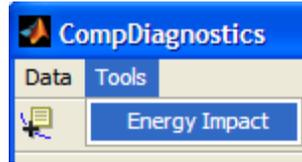


Figure H.12 Energy Impact Module Interface

The energy impacts are shown in the top panel in the form of a bar graph, as shown in Figure H.13. White bars indicate heating energy impact whereas bars in black indicate cooling energy impacts. The values are also displayed on the system status panel as shown in the figure below.

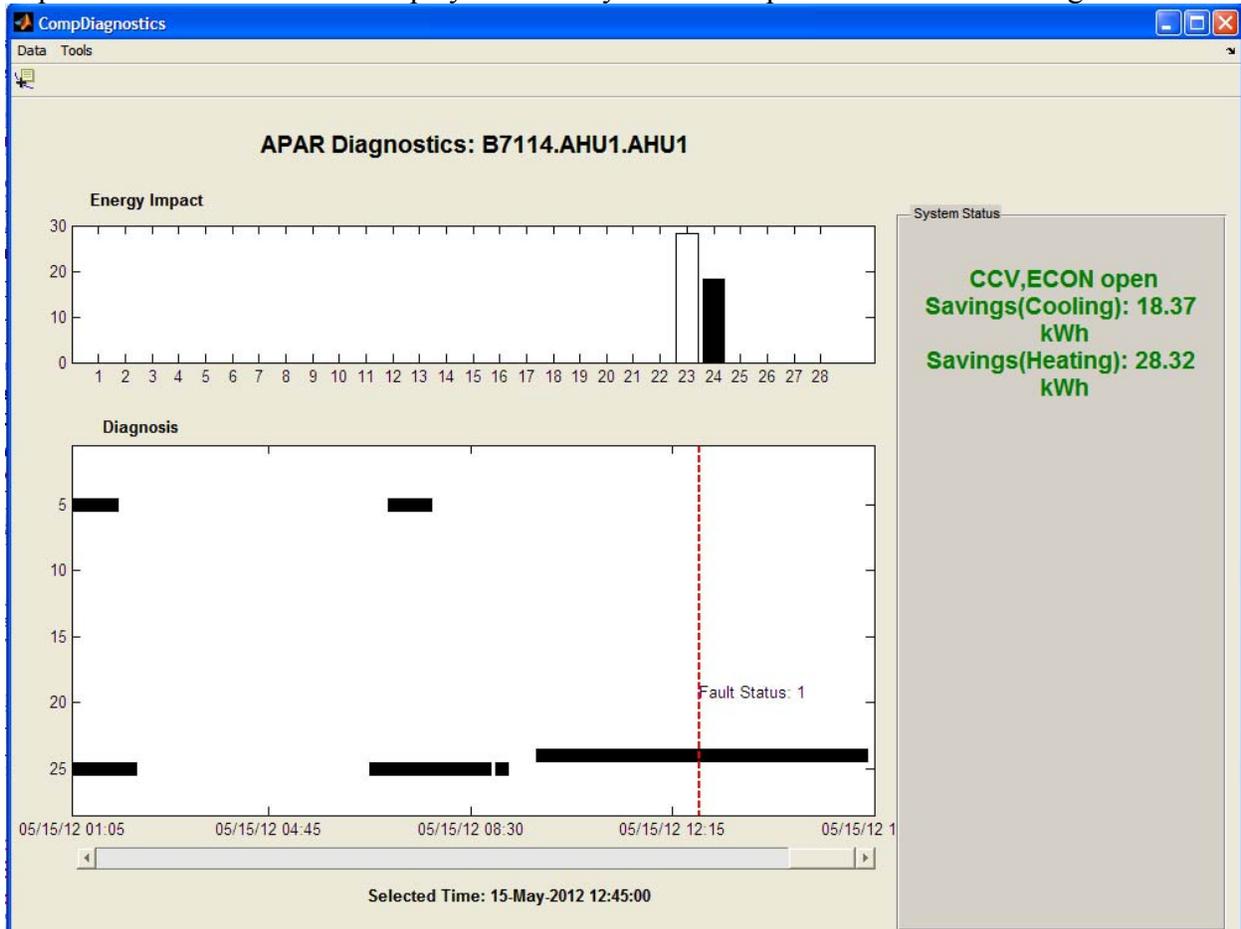


Figure H.13 Overview of the APAR Rules Tool.

### Sensitivity Analysis

The tool also allows the user to visualize results of HVAC operation sensitivity analyses and they can be accessed from the “Tools” menu. Figure H.14 shows how a user can access sensitivity analysis tools and model validation results from the iBED Viz main tool window.

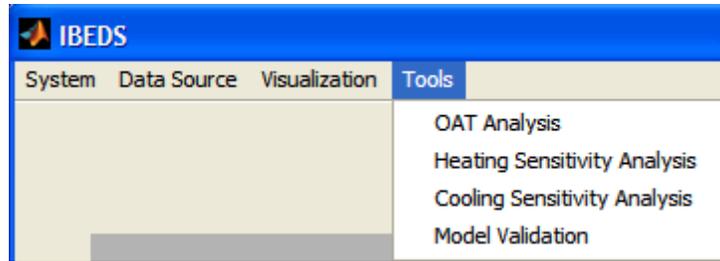


Figure H.14 HVAC Operation Sensitivity Analysis Tool Interface

Heating and cooling sensitivity analyses are implemented as separate tools that open in new windows as shown in Figure H.15 and Figure H.16

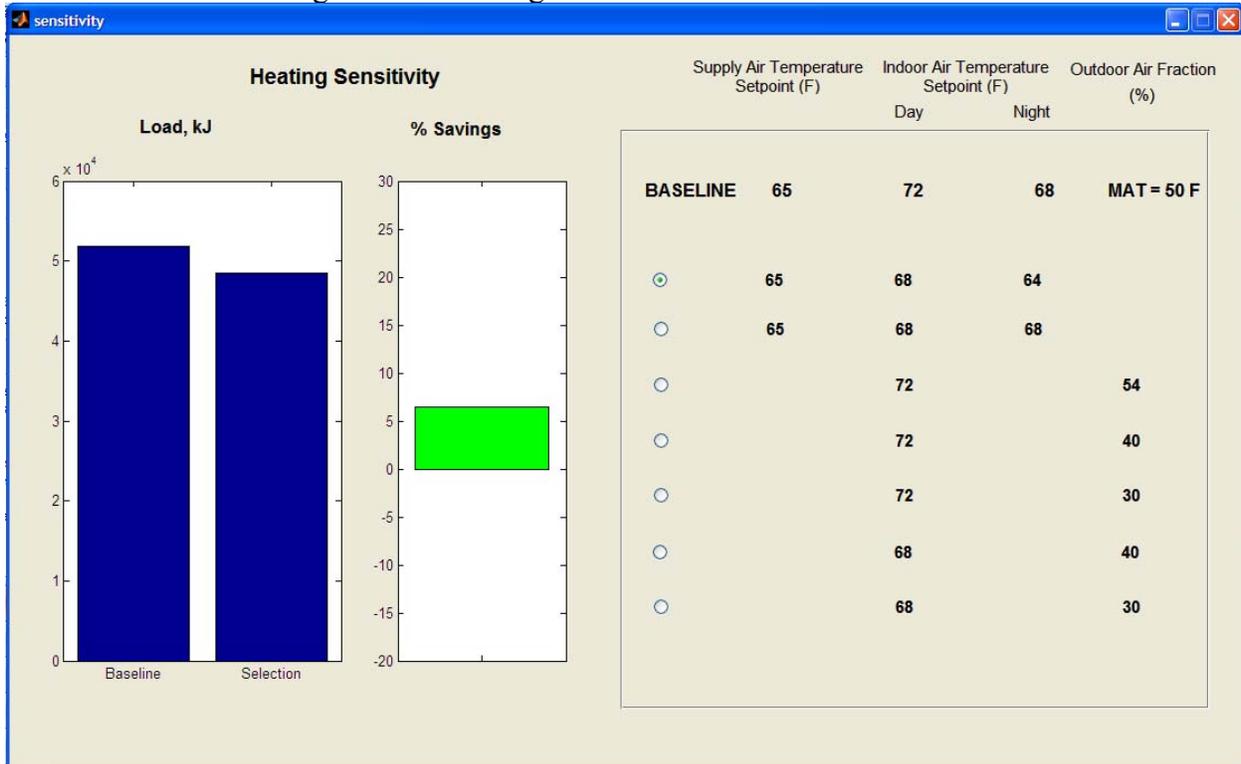


Figure H.15 Heating Sensitivity Analysis Tool.

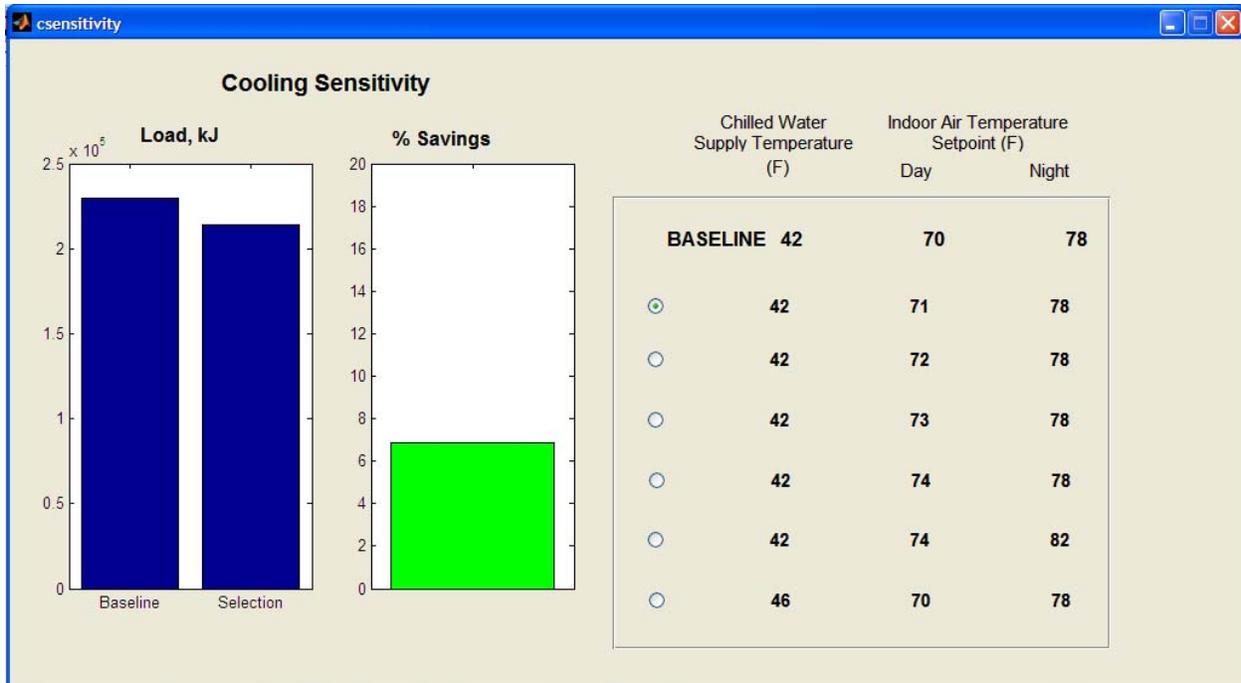


Figure H.16 Cooling Sensitivity Analysis Tool.

The sensitivity analysis tools allow the user to select an option and see energy impacts from the selected option compares to the baseline.

Additional features of the tool including diagnostics are described in details in the training documentation.

**References:**

1. <http://www.mathworks.com/products/matlab/>
2. House, J. M., Vaezi-Nejad, H. and Whitcomb, J. M. 2001. An Expert Rule Set for Fault Detection in Air-handling Units. *ASHRAE Transactions*. 107(1).

## APPENDIX I: DATA ACQUISITION SYSTEM

### Background

A Building Data Acquisition System (BDAS) was developed to acquire data in Building Automation Control (BAC) systems. The current version is able to acquire data from BACnet protocol compatible systems. In the future this software may be expanded to cover other protocols. The current version is based on the Building Control Virtual Test Bed (BCVTB) environment [1]. The content in this manual for BACnet Reader and BACnet Writer is from the manual of BCVTB [1].

### Function Supported

Up to the current stage, following functions are supported by the BDAS system:

- Get data from systems that support BACnet protocol
- Store data in a database

### Get Software

To get the software, user needs to download following items:

- BCVTB: It can be downloaded from <https://gaia.lbl.gov/bcvtb/Download>
- DataToSQLConverter: UTRC will provide this software.
- PostgreSQL: It can be downloaded at <http://www.postgresql.org/download/>
- JDBC Postgresql Driver: It can be downloaded from <http://jdbc.postgresql.org/download/postgresql-9.0-801.jdbc4.jar>

### Install Software

To install PostgreSQL on Windows, please follow the installation wizard. It is important to keep the password you set in a location because it will be used many times after the installation.

To install BCVTB, DataToSQLConverter and JDBC Driver, please follow these steps:

- Follow the BCVTB installation wizard to install BCVTB
- If the root directory of BCVTB is 'root', put the JDBC Driver in this directory 'root/lib/ptII/ptolemy/actor/lib/database/', note that this path works for BCVTB version 0.7.0, for other version this may slightly change.
- Open the file 'systemVariables-SYSTEM.properties' in 'root/bin', find the line starting with 'entry key=CLASSPATH', add the following to it (please modify the JDBC driver name if your version is different)  
%PTII%\nPtolenyactornlibndatabasenpostgresql-9.0-801.jdbc4.jar
- Unzip DataToSQLConverter, copy both 'GetTime.class' and 'StoreBACnetDataToDB.class' to this path 'root/lib/ptII/myActors'.
- Open file 'myActor.xml' in 'root/lib/ptII/myActors', add the following two items in the group entry  
<entity name="SendStorageTime" class="myActors.GetTime">  
<entity name="StoreBACnetDataToDatabase"  
class="myActors.StoreBACnetDataToDB">
- Then you are ready to go

## How to Use the software

### *Use of BACnet Reader in BCVTB*

The BACnetReader actor reads an xml configuration file to determine what data it needs to read from BACnet devices. This configuration file species the BACnet object types and their child elements, which can be other BACnet object types or BACnet property Identifier. The xml configuration file has the following syntax: It starts and ends with the following element.

```
<?xml version="1.0" encoding="utf-8"?>
<BACnet>
  <!-- Child elements are not shown. -->
</BACnet>
```

Figure I.1 BACnet Configuration File 1

BACnet requires at least one child element of the form i.e., the element name is Object, the attribute Type needs to be

```
<Object Type="Device" Instance="123">
  <!-- Child elements are not shown. -->
</Object>
```

Figure I.2 BACnet Configuration File 2

Device and the attribute Instance needs to be set to its instance number, which is a unique number that is assigned at the discretion of the control provider. Any Object element can contain other Object elements and other Property Identifier elements.

Thus, for example, the following can be set as a configuration file to read the 'Present Value' property of an 'analog output' object.

```
<?xml version="1.0" encoding="utf-8"?>
<BACnet>
  <Object Type="Device" Instance="123">
    <Object Type="Analog Output" Instance="1">
      <PropertyIdentifier Name="Present_Value"/>
    </Object>
  </Object>
</BACnet>
```

Figure I.3 BACnet Configuration File 3

Three types of objects need to be specified in the xml configuration file:

- BACnet. It is the root of the xml configuration file, every file has to start from <BACnet> and end at <BACnet>. Only contents specified between these will be recognized by BACnetreader.

- **ObjectType.** It is used to specify BACnet objects, including device objects and non-device objects. None device objects are attached to a device object, therefore, none device objects are specified at the child level of device objects, although they use the same name “ObjectType”. For device object, the name attribute should be “DeviceObjectType”, the instance attribute should be the device instance number. For non-device object, the name attribute should be the name of the object, for example, “AnalogInputObjectType”, the instance attribute should be the object instance number.
- **PropertyIdentifier.** It is used to specify the BACnet properties user want to query from BACnet server/device. They can be properties of both device object and non-device object. They should be at the child level of corresponding objects. The name attribute should be the name of the property.

An example for BACnet Reader is shown in Figure I.4. It shows a Ptolemy II system model that uses the BACnetReader actor. It has four output ports.

- errorSignal

If there were no errors in the previous data exchange, then this port outputs zero. Otherwise, the output is a non-zero integer.

- errorMessage

If there was an error in the previous data exchange, then this port outputs the error message that was generated by the BACnetReader actor. (The error messages that were generated by the BACnet stack are output of the consoleOutput port.

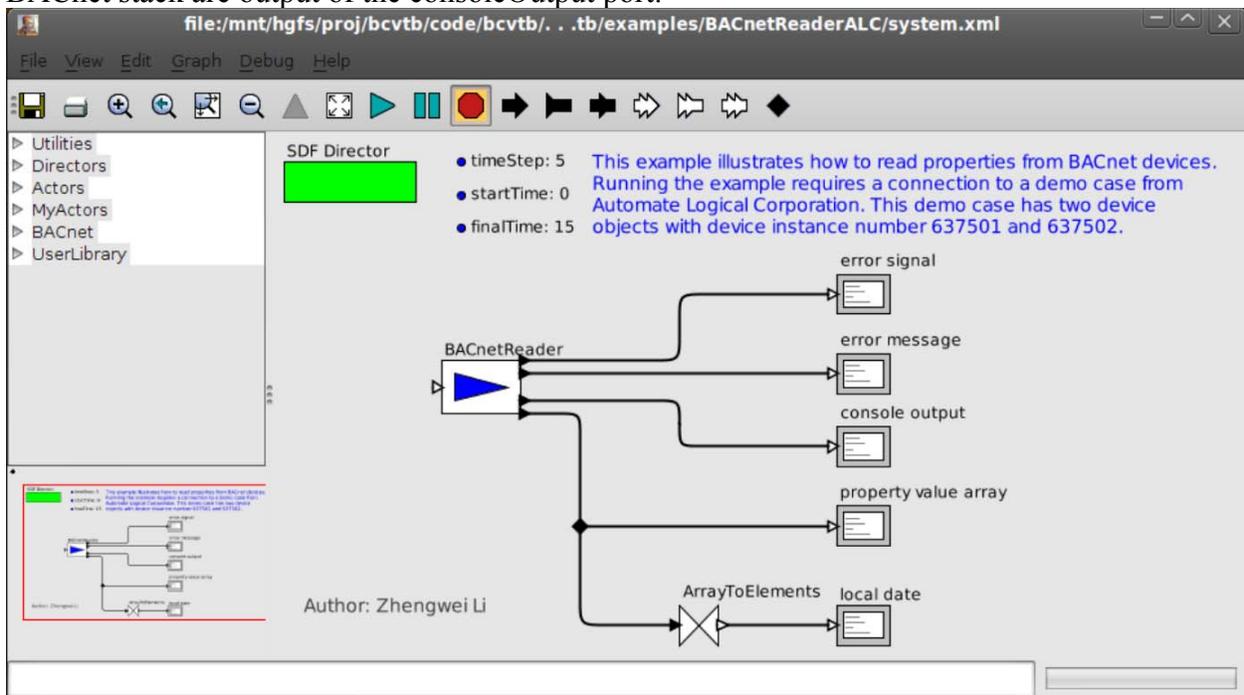


Figure I.4 BACnet Reader Example

- consoleOutput

This port outputs the standard output stream and the standard error stream of the executable that communicates with BACnet.

- `propertyValueArray`

This port outputs the values obtained at the last successful communication with the BACnet devices. If there was an error in the last communication, then the values from the previous time step will be output of this port. The output data type is an array whose elements are string representations of the BACnet properties that are read according to the configuration file. Elements can be extracted from this array using actors from Ptolemy IIs Actors-Array library.

To configure the BACnetReader, double-click on its icon and add the name of its configuration file. There is also a check-box called `continueWhenError`. If activated and an error occurs, then Ptolemy II will continue the simulation and the actor will output at its ports the last known value and the error message, unless the error occurs in the first step, in which case the simulation stops. If deactivated and an error occurs, then the simulation will stop, the error message will be displayed on the screen and the user is required to confirm the error message by clicking on its OK button. Thus, the user should select this box if the BCVTB should continue its operation when a run-time error, such as a network timeout, occurs.

### ***Use of Database Storage Function***

To store the data retrieved from Building Automation Control (BAC) system to database, four actors have to be used.

- `SendStorageTime`  
Found in `MyActors->SendStorageTime`
- `StoreBACnetDataToDatabase`  
Found in `MyActors->StoreBACnetDataToDatabase`
- `SQLStatement`  
Found in `Actors->DatabaseActors->SQLStatement`
- `DatabaseManager`  
Found in `Actors->DatabaseActors->DatabaseManager`

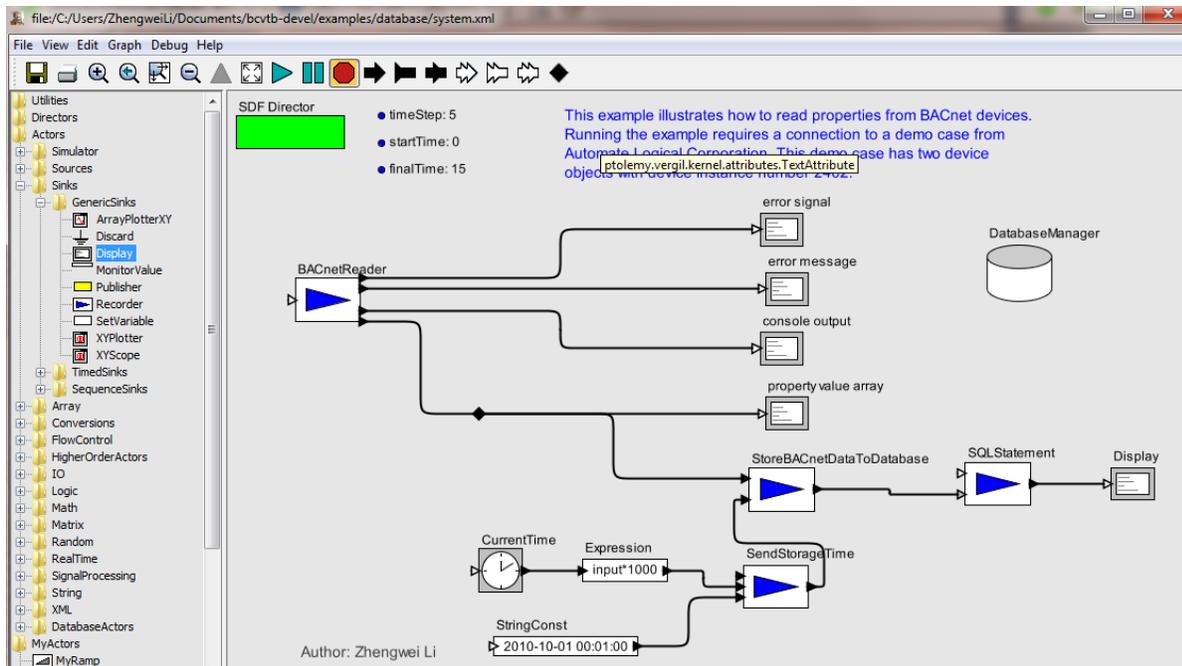


Figure I.5 Store BACnet Data to Database

SendStorageTime has two input ports: time and basetime. 'time' port receives the current simulation time from its start. Since the unit of synchronized time is seconds, it has to times by 1000 (to convert to milliseconds) before sent to the port. 'basetime' port receives the base from which the simulation starts. It is in 'YYYY-MM-DD HH:MM:SS' format. The output of SendStorageTime Actor is the current timestamp, in the same format as basetime.

StoreBACnetDataToDatabase actor has two input ports:input, time, and two parameters: tbnname, colname. Input port receives data coming from BACnetReader actor, time port receives data coming from SendStorageTime actor. Tbnname parameter specifies the table to which the data will be stored and colname parameter specifies the column names of the table. It is important to note that the column names are separated by comma, and the first column type has to be timestamp, because it is used to store time. The output of this actor is a SQL script.

SQLStatement actor has two input ports: trigger and query. If the direct is SDF director, trigger port does not need to be connected. Query port receives the SQL script. The output is the response from database, it could be 'OK' or 'failed'. It could be displayed if the output port is connected to a 'Display' actor.

Database manager actor is a necessary component for all database use model. It has two parameters; database and userName. 'Database' specifies the name of the database, if it is a PostgreSQL database, it should be like 'jdbc:postgresql://localhost:5432/dbname', userName is the owner of that database. During the execution, a user also needs to type in the password for that particular database and username.

## Reference

[1]

<http://simulationresearch.lbl.gov/bcvtb/>



To conduct a full building energy simulation, property information about HVAC system and power system is also necessary. The schema generalizes all equipment with an equipment entity, and differentiates the usage with a function attribute. Then based on where the equipment is located, the system level equipment is categorized into one of three categories: primary system, secondary system and terminal system. Component level equipment is categorized into “component”. The equipment entity is shown in Figure J.3. Primary system, secondary system, terminal system and equipment are shown in Figures J.3 and J.4, respectively.

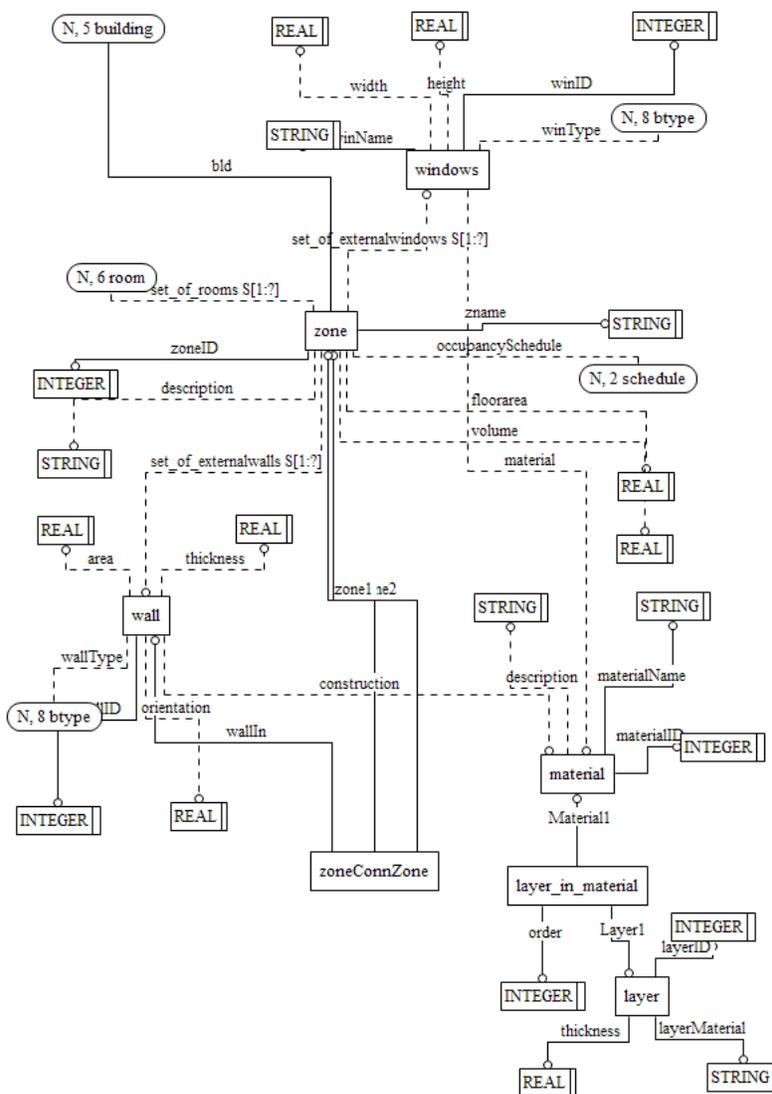


Figure J.2 Relationship between Zone and Room, Wall, Window and Material

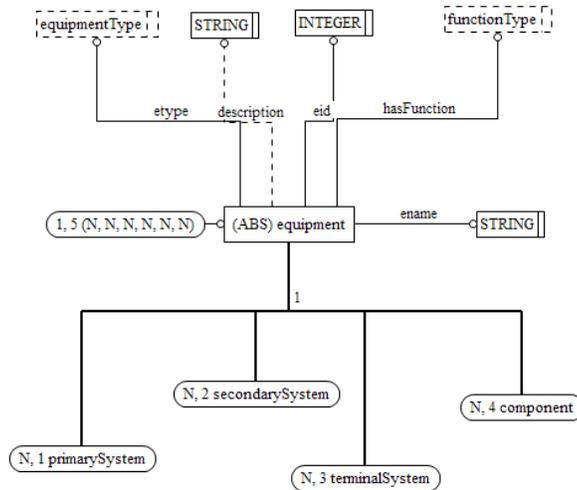


Figure J.3 Equipment

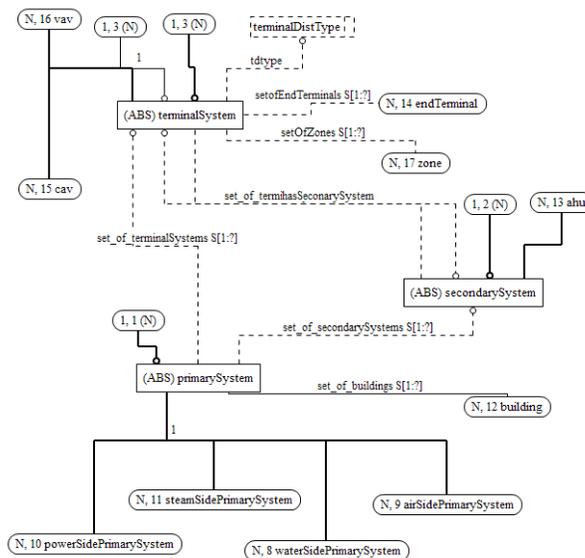


Figure J.4 Primary, Secondary and Terminal System

*b) Operational Information*

The building operational information refers to the information coming from building BMS system including all sensor data, command signals and control set points. This is also how operational data is categorized. In each category (sensor, set point, and control signal), entities are further separated based on the physical definition (temperature, velocity, volume flow rate, etc.). The sensor schema developed based on this categorization is shown in Figure J.5. To store the dynamic value of a sensor, timestamp is used as attribute at the smallest category level. As an example, Figure J.6 shows the schema for temperature sensor.

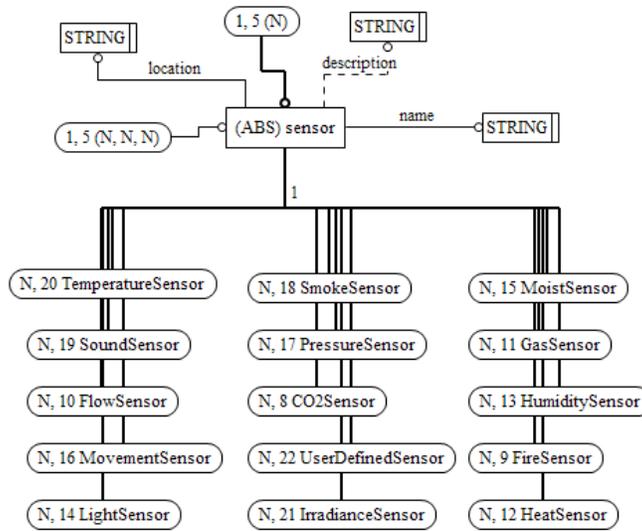


Figure J.5 Sensor Schema

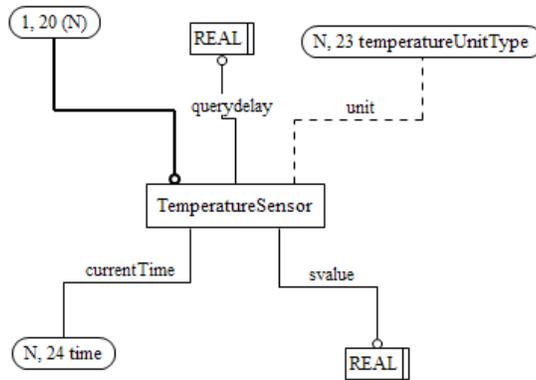


Figure J.6 Temperature Sensor Schema

*c) Simulation Information*

To store the output from real time energy simulation, the following entities are used: simulationdata, temperaturesim, flowsim, humiditiesim, loadsim, pressuresim, factorsim and efficiencysim. The schema for Simulationdata is shown in Figure J.7.

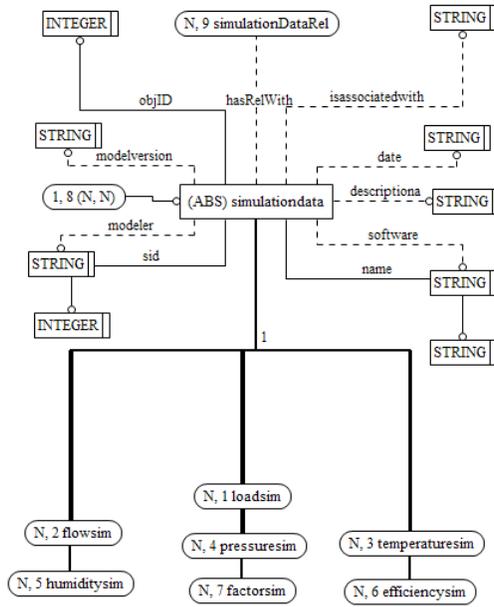


Figure J.7 Simulation Data

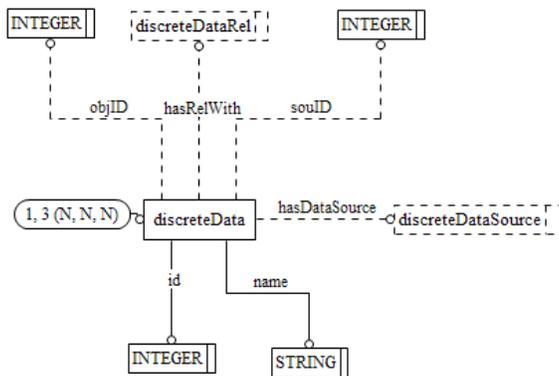


Figure J.8 FDD Discrete Data

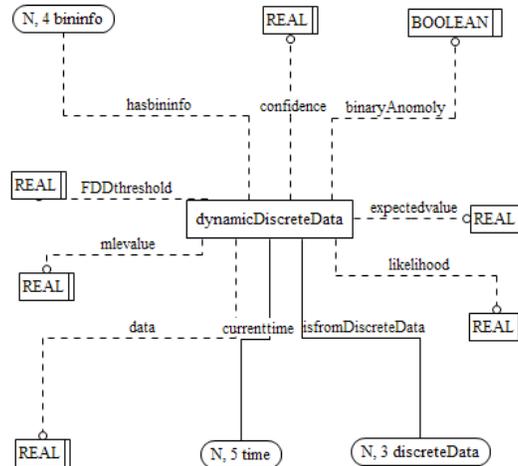


Figure J.9 FDD Dynamic Discrete Data

#### d) FDD Information

A static table that stores the FDD data points and a dynamic table that stores the FDD outputs are the minimal configuration requirements for FDD information. In the current schema, the ‘discretedata’ entity is used for storing the FDD static information, the ‘dynamicDiscreteData’ entity is used to store the FDD dynamic information, which are shown in Figures J.8 and J.9, respectively.

#### 2). Automatic Simulation Code Generation

Once the BIM database is set-up, the static information is collected through Building Information Modeling Test Bed (BIMTB), a middleware which reads building information from a neutral format file (IFC/gbXML), and stores that data in the centralized BIM database. An IFC View Definition, or Model View Definition (MVD), defines a subset of the IFC schema, which is needed to satisfy one or many exchange requirements of the architectural, engineering and construction (AEC) industry. This is also one of the requirements for successful information exchanges. The MVD for architecture and HVAC relevant information is shown in Figures J.10 and J.11, respectively.

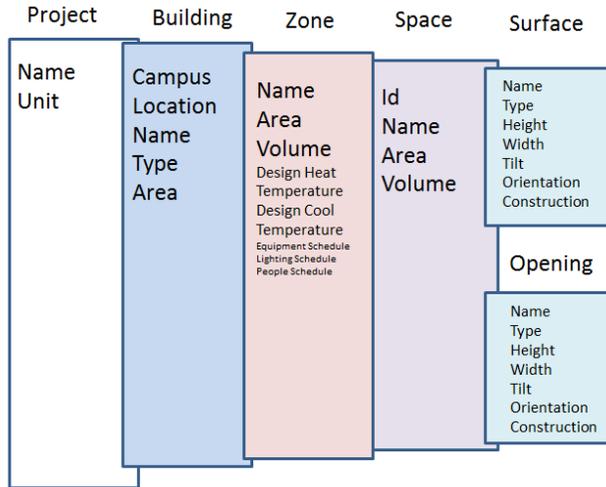


Figure J.10 MVD for Architecture

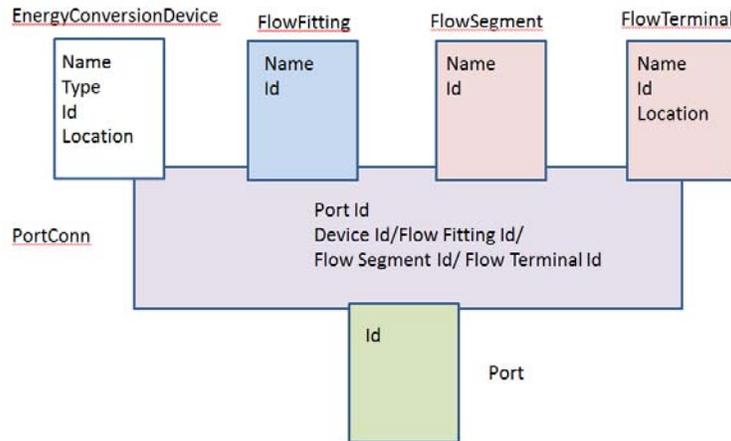


Figure J.11 MVD for HVAC Systems

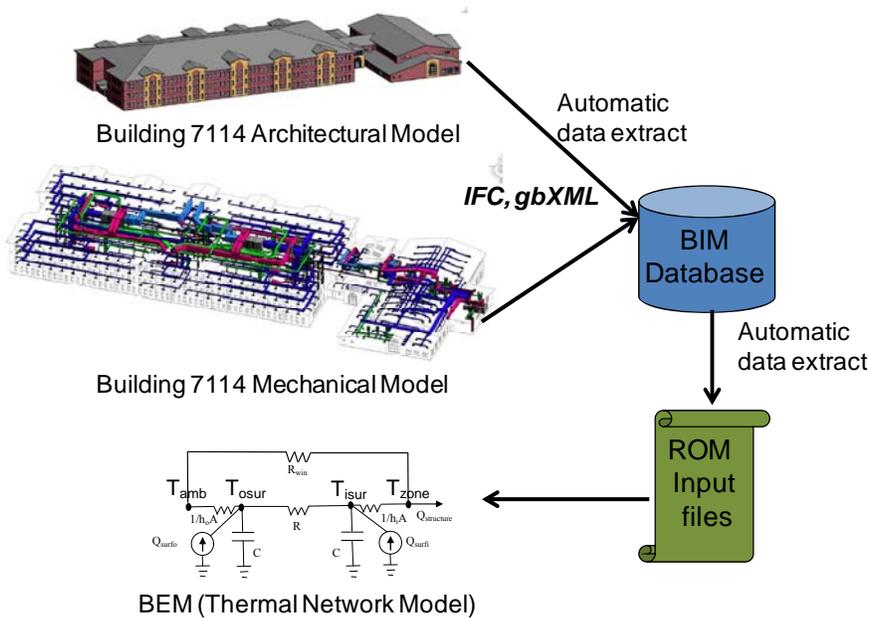


Figure J.12 BIM to BEM Flow Chart

Figure J.12 shows the flow chart from BIM to Building Energy Modeling (BEM) process. The information from both Revit architecture and mechanical drawings were exported to IFC and gbXML files. The unique difficulties of Autodesk Revit are: (1) Revit does not support the translation of a HVAC zone to a IFC zone; (2) mapping between a zone and an envelope surface does not exist in the IFC file; (3), mapping between a zone and a HVAC equipment does not exist in IFC file; and (4) Native translation of Revit model to IFC file does not contain the connection between flow terminals and equipment. To address the above problems, following approaches are proposed:

- Architectural information is read from a gbXML file, which can also be exported given a Revit model
- HVAC information is read from a refined Revit HVAC model through GraphiSoft plugin [1] for Revit MEP 2011.
- The link between the architectural information and HVAC information is established through the geometry attribute, where the coordinates of each flow terminal are mapped to its corresponding zones.

Beside the issues with HVAC zones, the thermal properties for each material layer can be only entered manually as a single thermal resistance value after calculated outside the software. Input files for both building envelope and HVAC models are automatically generated from the data extracted from IFC/gbXML files.

#### References:

- [1] Graphisoft, <http://www.graphisoft.com/>

## **APPENDIX K: RESPONSE TO ESTCP IPR ACTION ITEMS**

*Action Item:* A White Paper was requested at the October 2011 IPR to address the maturity of building energy management systems and what follow on activities should occur after this project as the next step towards widespread deployment of the technology across DoD. Recommend additional types of demonstrations needed to advance the technology and its adoption by DoD. Please submit the White Paper by Dec 15, 2011.

### **Project Summary**

The United Technologies Research Center is demonstrating a building energy management system that employs advanced methods for whole-building performance monitoring combined with statistical methods of learning and data analysis to enable identification of both gradual and discrete performance degradation and faults. The system assimilates data collected from multiple sources including drawings, reduced-order models (ROM) and measurements, and employ advanced statistical learning algorithms to identify patterns of anomalies. The results are presented graphically in a manner understandable by a facilities manager. The demonstrated technology is targeted at commercial buildings that use building energy management systems. We expect to be able to demonstrate 20% savings for building energy consumption by improving facility manager decision support to diagnose energy faults and prioritize alternative, energy efficient operation strategies. We also expect to demonstrate scalability of the solution by applying load estimation techniques and reduced-order models for the building and HVAC systems, reducing the need for developing specific, detailed models for each building. The specific technical objectives of the project are 1) to demonstrate 10% building energy savings by providing the facility engineers with actionable energy fault information to identify and correct poor system performance, and 2) to demonstrate an additional 10% energy savings by identifying alternative energy system operation strategies that improve building energy performance. The demonstration is being conducted in buildings at the Naval Station Great Lakes. The facility building management systems are being extended to incorporate the energy diagnostics and analysis algorithms, producing systematic identification of alternative, energy efficient HVAC operation strategies.

### **Response: Scalable deployment of Advanced Building Energy Management Systems**

During the demonstration process at Naval Station Great Lakes, the maturity of the different technology elements have been assessed with gaps identified that will impact the successful deployment of a building energy performance monitoring and diagnostics system. After the completion of the Naval Station Great Lakes demonstration, it is recommended that the following list of activities should occur to ensure widespread technology deployment at the DoD.

- 1) Develop low cost and scalable building energy monitoring systems.
- 2) Implement a robust and scalable middleware for DoD buildings.
- 3) Deploy a secured DoD network for energy efficient buildings.
- 4) Integrate Energy Human Machine Interface (eHMI) applications for DoD building facility operations.
- 5) Implement a scalable process for DoD building data collection.

The following paragraphs provide the rationale and details for these recommendations.

### **Low cost and scalable building energy monitoring systems**

The instrumentation required to support the advanced building energy management system has a cost that will challenge broader deployment of the aBEMS in other DoD buildings. The instrumentation costs include:

- material costs (i.e., sensors, thermal and electrical meters)
- installation costs
- system commissioning costs
- building management system points mapping costs

The advanced building energy management system uses sensor information from existing building management systems wherever possible. Additional instrumentation is added to provide run-time model inputs, calibrate models and to do energy performance monitoring and diagnosis. A BMS with BACnet (A Data Communication Protocol for Building Automation and Control Networks) gateway is a required to implement the technology. The additional measurements required to track key building energy performance metrics are electrical power sub-metering and thermal energy consumption for cooling and heating. After the sensors/meters have been installed, there is currently considerable time required to handle issues related to data quality, system commissioning and mapping points into the BMS. This is due to the fact that current BMS in existing buildings are not designed for building performance monitoring and energy diagnostics. It is desirable that the sub-metering system and associated points should be considered and included in the BMS at the design stage.

A low cost and scalable building energy monitoring system is important for building commissioning that will span the entire building life cycle. It will reduce the commissioning cost and increase the fidelity of energy waste identified during the commissioning process. The payback time of the building commissioning process will be significantly decreased due to the proposed low cost monitoring system. High instrumentation costs that have occurred in the current ESTCP demonstration projects need to be addressed to enable broad DoD deployment of the aBEMS. Specific gaps are identified as follows:

- Lack of a guideline for energy monitoring systems (including electric and thermal) for both new building design and retrofit of existing buildings.
- Lack of low cost, scalable building electrical and thermal energy sub-metering
- Lack of systematic and robust tools and methods to design a building energy sensor network that includes both physical and virtual sensors.
- Lack of scalable method for automated sensor diagnostics.
- Lack of a robust and universal data management system for DoD buildings.

To address these gaps, the following key technologies need to be developed and tested:

- Develop a comprehensive guideline for the deployment of energy monitoring systems in DoD buildings.
- Demonstrate low cost, scalable building electrical and thermal energy sub-metering
- Automated sensor diagnostics that combine heuristic rules, physical based models and data mining algorithms
- Virtual sensors derived from physical based models and nonintrusive load monitoring in commercial buildings.
- Universal data management systems that include data acquisition and automated point mapping into the BMS.

Figure K.1 illustrates the concepts of low cost and scalable building energy monitoring system.

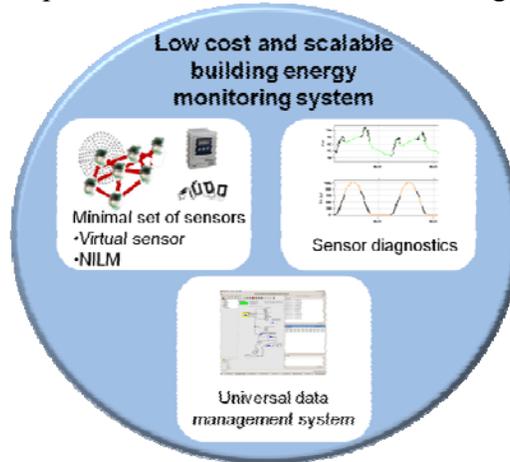


Figure K.1 A Schematic Diagram of Low Cost and Scalable Building Energy Monitoring System

**Robust and scalable middleware for buildings**

Existing data management systems included with a building BMS are fragile and control-vendor specific. A universal middleware is necessary to deploy the key elements in the aBEMS in DoD buildings. This middleware will significantly reduce the deployment time required for data acquisition, data storage, visualization and service application integration. In addition, the use of middleware to enable distributed computing and storage at a sensor or central node level has the potential to provide faster response times and fault tolerance. Figure K.2 shows a schematic diagram for a robust and scalable middleware.

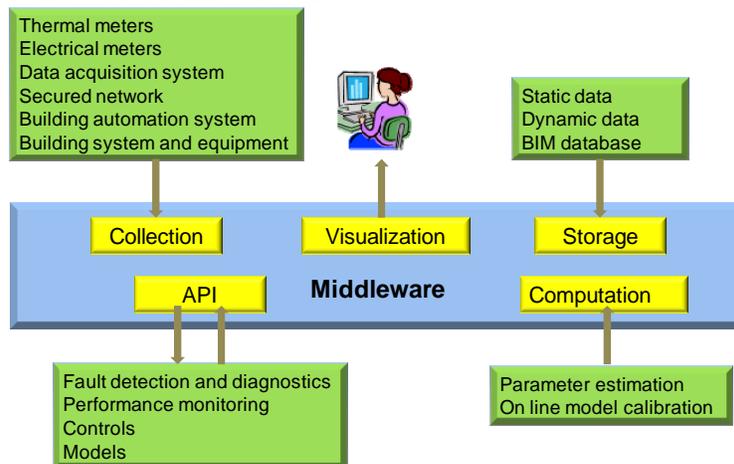


Figure K.2 Middleware Schematic Diagram

In the Naval Station Great Lakes demonstration project, real time building operational data is collected through a BACnet gateway by using the open source software BCVTB<sup>21</sup>. A Building Information Model (BIM) supported database was prototyped and used to store both building

<sup>21</sup> Building Control Virtual Test Bed <http://simulationresearch.lbl.gov/bcvtb/>

static data (e.g., model parameters, HVAC configuration, etc.) and building dynamic operational data (e.g. temperature, energy). The following gaps are identified:

- Lack of a universal data collection system where data can be extracted and retrieved through other industry standard communication protocols (e.g., LonWorks, Modbus, etc.).
- Lack of a secure, scalable and industry standard oriented storage mechanism for both static and real time dynamic building operational data.
- Lack of a standard Application Programming Interface (APIs) that enable applications to programmatically extract data from the system, perform calculations outside of the middleware and finally write data back to the middleware. Examples of such applications are building performance simulation programs, Fault Detection and Diagnostics (FDD) tools, visualization, controls and optimization tools.
- Lack of common computational services such as on-line parameter estimation and on-line model calibration that can be deployed as part of the middleware.

To address these gaps, it is recommended that the following activities should occur after this project:

- Extend a BACnet compatible data acquisition system to cover the other industry standard communication protocols.
- Develop a database structure that enables rapid mapping and use of both static building information and real time dynamic operational data during the design and operational phases of a building lifecycle. This structure should be tested in a variety of buildings with different types and sizes.
- Develop a services-based architecture to support the data exchange APIs and computational services.

### **Deployment of a secured DOD network for energy efficient buildings**

The IT infrastructure and security requirements at Naval Station Great Lakes presented a significant challenge for the project. Limited remote access to the demonstration buildings increased both the time and cost of development and testing the aBEMS. Network security constraints at the demonstration site prevented the team from having broadband access to the PCs at Naval Station Great Lakes. An ISDN line was set up to access the computer at Building 7230. However, the ISDN connection speed is prohibitively slow for the massive data transfer (e.g. >1 GB of operational data for one month) required by this project. In the case of Building 7113/7114, there was no possibility for remote access. This presented a significant challenge for coding, debugging and testing. Another issue is related to a centralized BMS. Currently, Great Lakes does not have a centralized BMS. Ideally, to deploy the aBEMS for all the buildings at Great Lakes, only one additional PC should be required to monitor the performance for all the buildings.

A secured DoD network is necessary to improve energy efficiency in buildings across the DoD. A secured and integrated network will facilitate the deployment of energy efficient technologies such as the advanced building energy management system prototyped in this project, automated demand response, and smart meters etc. In addition, this secured network will make the building information visible across the DoD so that building performance benchmarking will be possible. Building performance benchmarking data is extremely useful for facility managers to understand

their building behaviors in the comparative context of peer buildings. At the same time, Real-time energy meter data can be provided to the building tenants to visibly show how their facilities are performing and give them an incentive to reduce energy consumption. Recently, the team has been made aware of a project executed through Naval District Washington to develop a secured DoD network that will make real time building meter data visible. Currently this effort is focused only on total building energy consumption and would need to be expanded to include building energy sub-metering necessary to support the advanced building energy management system.

The following gaps are identified:

- Lack of a specification to define a secured DoD network for energy efficient buildings
- Lack of a secured and integrated network that links all the BMS in individual buildings to a centralized BMS.
- Lack of a systematic way to collect and publish building energy usage data, including total building energy usage (i.e., EUI), subsystems and components level metering data, from all DoD commercial buildings via a secured network.

To address these gaps, it is recommended that the following activities should occur after this project:

- Establish a secured and integrated DoD network for building applications.
- Collect and share building energy usage data via a secured network.

#### **Energy Human Machine Interface (eHMI) applications for DoD building facility operations**

The eHMI provides a graphics-based visualization of building performance monitoring and energy diagnostics. The approach to make the building information visible and actionable for the facility team is critical to better operate the building and reduce energy consumption in buildings. This visible and actionable information helps to decrease the time needed for building system maintenance and upgrades. The aBEMS provides real time performance monitoring and energy diagnostic functionality. A user friendly and modular user interface (UI) is being developed to facilitate navigation through a potentially large database. Gaps are listed as follows:

- Lack of a UI such that users can rapidly build their own visualization screens containing charts and 3D graphics.
- Lack of functionality for generating comprehensive reports that can be sent in real time to the facility team.
- Lack of a standard and common building operation interface that can be integrated with the BMS in all DoD buildings

To address these gaps, it is recommended that the following activities should occur after this project:

- Develop a flexible and extensible UI that enables rapid development by common DoD facility users.
- Develop a standard mobile application for the aBEMS. This will make the recommendations provided by the aBEMS immediately visible and actionable.

#### **A scalable process for building data collection**

Collecting building data for building performance monitoring, energy diagnostic and controls is time-consuming and inefficient in current building industry practice. This project started to



**Action Item: Provide recommendations for DoD to consider when integrating building energy management systems with emerging microgrid technologies and practices such as demand management.**

The same approaches that are currently used for building energy management systems at the demand side can be applied for supply and storage side. These approaches include but are not limited to fault detection and diagnostics, optimal control with receding horizon, stochastic consideration of loads and weather forecasts.

Demand, supply and storage integration (i.e., a holistic consideration to energy management in buildings) could be a straightforward extension to existing approaches and existing building energy management systems (BMS). The integration could bring additional savings and security of supply to critical loads. For example, if the utility increases prices or sends a request for peak shaving, the integrated energy management system can decide whether to produce more, use stored energy, or temporary cut demand. It will depend on customer preferences and requirements, economic incentives, forecasts (e.g. solar or wind, and loads), and the security of supply side.

Another way to control the microgrid is a SCADA (Supervisory Control and Data Acquisition)/PLC (Programmable Logic Controllers) system. This is an industry standard for controls of distributed power generation. One of the advantages of using a SCADA system is that utility and grid networks also use SCADA for sub-station control and utility power generators use SCADA for power station control and wind farm control etc. The grid operators communicate with the power generation SCADA for monitoring and control purposes. It is well known that utility providers tend to be very conservative and adoption of new standards, particularly those which are not directly related to safety, tends to take a long time. In the near term, using SCADA is possible the better way to integrate the demand side with the smart grid.

In terms of best practice, if there is a microgrid with a PLC/SCADA system, it would be better to use the SCADA rather than the BMS to control electrical loads. Particularly if there is a ramp down or a control sequence required because currently there is a lot more flexibility in programming of SCADA than there is in BMS systems. However, if it is just an on/off control, a contactor in the BMS panel, linked to some simple logics in the BMS programming would do the job.

**Action Item: Describe the general approach to energy management system calibration using performance data over time to learn and adjust.**

The reference model used in the building energy management system can be automatically calibrated using the approach presented in O'Neill (2012)<sup>22</sup>. The brief summary is as follows:

The model calibration process relies heavily on characterizing parametric influences on the outputs of the model. This analysis was performed by sampling all parameters of the model around their nominal value to create a database of output data which was used to calculate the

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<sup>22</sup> O'Neill, Z. D., B. Eisenhower, V. Fonoferov and T. Bailey. 2012. Calibration of a Building Energy Model Considering Parametric Uncertainty. *ASHRAE Transactions*, 118(2). *ASHRAE Annual Meeting*. San Antonio, TX. Jun 23–27, 2012.

sensitivity of these outputs to parameter variation as well as to derive an analytic meta-model based on this model data. Once the most influential parameters (on the order of 10 to 20) of the model are identified, an optimization can be performed (using the meta-model) in order to identify parameter combinations that produce the best fit to measured data. Only 10-20 of the most influential input parameters instead of thousands were optimized during the optimization/calibration process to avoid the issue of *over fitting* the model.

***Action Item:* Describe specifications DoD should publish in appropriate standards documents addressing topics such as building size, numbers/types of meters, instrumentation, communications protocols, integration of native systems, etc.**

DoD should start to publish the guidelines and standards in the following areas to facilitate the deployment of advanced building energy management systems across DoD buildings and facilities.

- A design guideline to determine the minimum set of sensors/meters needed to deploy a comprehensive energy monitoring system for both new construction and retrofit of existing buildings. This guideline should include a check list of sensors/meters and decision flow charts for different HVAC systems.
- A guideline to establish a secured and integrated DoD network for building applications.
- A standard to share building energy usage data via a secured network using native communication protocols such as BACnet and LonWorks etc.
- A standardized process to automatically collect building information from available references and transfer them to building energy applications such as building energy models.

***Action Item:* Discuss issues and insights regarding the implementation of energy management systems within the DoD information technology infrastructure.**

The IT infrastructure and security requirements at Naval Station Great Lakes presented a significant challenge for the project. Limited remote access to the demonstration buildings increased both the time and cost of development and testing the aBEMS. Network security constraints at the demonstration site prevented the team from having broadband access to the PCs at Naval Station Great Lakes. An ISDN line was set up to access the computer at Building 7230. However, the ISDN connection speed is prohibitively slow for the massive data transfer (e.g. >1 GB of operational data for one month) required by this project. In the case of Building 7113/7114, there was no possibility for remote access. This presented a significant challenge for coding, debugging and testing. Another issue is related to a centralized BMS. Currently, Great Lakes does not have a centralized BMS. Ideally, to deploy the aBEMS for all the buildings at Great Lakes, only one additional PC should be required to monitor the performance for all the buildings.

A secured DoD network is necessary to improve energy efficiency in buildings across the DoD. A secured and integrated network will facilitate the deployment of energy efficient technologies such as the advanced building energy management system prototyped in this project, automated demand response, and smart meters etc. In addition, this secured network will make the building information visible across the DoD so that building performance benchmarking will be possible. Building performance benchmarking data is extremely useful for facility managers to understand their building behaviors in the comparative context of peer buildings. At the same time, Real-

time energy meter data can be provided to the building tenants to visibly show how their facilities are performing and give them an incentive to reduce energy consumption. Recently, the team has been made aware of a project executed through Naval District Washington to develop a secured DoD network that will make real time building meter data visible. Currently this effort is focused only on total building energy consumption and would need to be expanded to include building energy sub-metering necessary to support the advanced building energy management system.

***Action Item:* In your Final and Cost & Performance Reports, recommend guidelines for how the demonstrated technology could apply to new construction and how it could apply in retrofit applications, particularly in terms of system controls and enabling sensors to collect data for diagnostics.**

A design guideline to determine the minimum set of sensors/meters needed to deploy a comprehensive energy monitoring system for both new construction and retrofit of existing buildings is recommended. This guideline should include a check list of sensors/meters and decision flow charts for different HVAC systems. This guideline also should follow the following industry guidelines:

- Specifications Guide for Performance Monitoring Systems (<http://cbs.lbl.gov/performance-monitoring/specifications/>)
- ASHRAE: Performance Measurement Protocols for Commercial Buildings.
- National Science & Technology Council, Committee on Technology. Sub-metering of building energy and water usage - Analysis and recommendations of the subcommittee on buildings technology research and development.

For the new construction buildings, it is recommended that the owners and designers should pay attention to the following items:

- Electrical circuits design to make sure the sub-metering is possible at the subsystem and component level.
- BMS design to select a native communication protocol such as BACnet to ensure the data communication and acquisition via a secured network across different subsystems in buildings.

In retrofit applications, it is possible that the existing BMS is not compatible with native communication protocols. Data acquisition will have to be tunneled through a middleware that is capable of extracting data via a specific server such as a BACnet server and an OPC server.

***Action Item:* In your Final and Cost & Performance Reports, include a discussion about the quantification and management of increased risks to building operations caused by increasing complexity of the building system by metering and sub-metering a building.**

In the advanced building energy management system, all the meters (thermal and electrical) are mapped and integrated with the existing BMS system. The mapped information can be graphically displayed through the existing BMS's interface (e.g., Siemens' Insight). Meter locations and real time meter data are visible to the facility manager and building operator. Energy diagnostics module in the advanced building energy management system also detects, diagnoses and flags faults from the metering sub-system.

***Action Item:* In your Final and Cost & Performance Reports, discuss what types of policies DoD should implement to ensure building metering and sensors are adequate to use advanced management systems.**

It is recommended that DoD should develop a design guideline to determine the minimum set of sensors/meters required to deploy a comprehensive energy monitoring system for both new construction and retrofit of existing buildings. DoD should begin to mandate that DoD facilities to install energy meters at the intermediate level recommended by the ASHRAE performance measurement protocols<sup>23</sup>. This will support an enhanced level of understanding of the building performance and to identify possible areas of performance improvement through the use of advanced building energy management system. Energy meters should include:

- HVAC total electric
- HVAC fan electric
- Chiller plant electric
- Nonelectric heating (other fuel)
- Electric heating, when significant electrical that is present
- Indoor lighting total electric
- Miscellaneous electric (Plug loads)
- Thermal BTU meters for chilled water loop and hot water loop
- Thermal BTU meters for hot water loop

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<sup>23</sup> ASHRAE. 2010. Performance Measurement Protocols for Commercial Buildings

## APPENDIX L: RESPONSE TO ESTCP TEST BED 10

### 1. What is the baseline/standard in most DoD buildings/installations for the demonstrated technology? (nationally?)

The baseline/standard in most DoD buildings/installations for the demonstrated Advanced Building Energy Management System (aBEMS) is described in five different areas in terms of gaps as follows:

- Building Energy Monitoring System:
  - Lack of a guideline for energy monitoring systems (including electric and thermal) for both new building design and retrofit of existing buildings.
  - Lack of low cost, scalable building electrical and thermal energy sub-metering
  - Lack of systematic and robust tools and methods to design a building energy sensor network that includes both physical and virtual sensors.
  - Lack of scalable method for automated sensor diagnostics.
  - Lack of a robust and universal data management system for DoD buildings.
- Middleware for Buildings:
  - Lack of a universal data collection system where data can be extracted and retrieved through other industry standard communication protocols (e.g., Lonworks, Modbus, etc).
  - Lack of a secure, scalable and industry standard oriented storage mechanism for both static and real time dynamic building operational data.
  - Lack of a standard Application Programming Interface (APIs) that enable applications to programmatically extract data from the system, perform calculations outside of the middleware and finally write data back to the middleware. Examples of such applications are building performance simulation programs, Fault Detection and Diagnostics (FDD) tools, visualization, controls and optimization tools.
  - Lack of common computational services such as on-line parameter estimation and on-line model calibration that can be deployed as part of the middleware.
- Secured DOD Network for Energy Efficient Buildings
  - Lack of a specification to define a secured DoD network for energy efficient buildings.
  - Lack of a secured and integrated network that links all the BMS in individual buildings to a centralized BMS.
  - Lack of a systematic way to collect and publish building energy usage data, including total building energy usage (i.e., EUI), subsystems and components level metering data, from all DoD commercial buildings via a secured network.
  - Energy Human Machine Interface (eHMI) applications for DoD building facility operations.
  - Lack of a UI such that users can rapidly build their own visualization screens containing charts and 3D graphics.
  - Lack of functionality for generating comprehensive reports that can be sent in real time to the facility team.
  - Lack of a standard and common building operation interface that can be integrated with the BMS in all DoD buildings
- A Scalable Process for Building Data Collection

- Lack of a systematic process to automatically extract building reference data from industry standard data files (e.g., IFC and gbXML).
- Lack of a robust, scalable and standardized way to collect and store both static and operation dynamic data throughout a building lifecycle.
- Lack of a robust and scalable way to automatically transfer building information from legacy drawings to building energy applications.

This list aims to help the reader to understand clearly what the gaps are within the current baseline/standard that may preclude this technology from being applied or what similar building features and systems make this technology readily applicable.

## 2. What is the “state of the art” today?

The state of the art today is summarized as follows:

- The aBEMS augments an existing BMS with additional sensors/meters and uses a reduced-order building reference model and diagnostic software to make performance deviations visible.
- Existing systems do not provide a viable means to quantify the value of a proposed HVAC operation strategy, or a methodology to quantify the value of different strategies. This system employs a physics-based ROM based sensitivity study that is useful to estimate the economic value of different HVAC operation strategies.
- Compared to purely rule-based technologies such as PACRAT<sup>a</sup>, this system uses a scalable physics based ROM together with data mining such as probabilistic graphical network and other data mining techniques for rigorous energy diagnosis.
- Existing systems do not provide a means to calculate and visualize the energy impact due to faults.

## 3. How will the project advance the state of the art?

Refer to answers to Question 2.

## 4. What are the technical and economic performance objectives?

The objective of this project is to demonstrate an advanced building energy management system that enables facility managers to visualize building energy performance, diagnose building energy faults, and assess alternative, energy efficient HVAC operation strategies. The technical and economic performance objectives are described as follows:

- >20% reduction in building total energy consumption (over baseline)
- >15% reduction in building peak demand energy (over baseline)
- >20% reduction in building total equivalent CO<sub>2</sub> emissions (over baseline)
- >10% reduction in HVAC equipment energy consumption (over baseline)
- >10% reduction in lighting or plug loads (over baseline)
- Predicted building loads difference (absolute error) between detailed model and ROM within +/- 10%
- Overall building energy consumption accuracy within +/-15% (ROM vs. measurement)

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<sup>a</sup> Friedman, H. and M.A. Piette, *A Comparative Guide to Emerging Diagnostic Tools for Large Commercial HVAC Systems*, LBNL Report 48629, LBNL, Berkeley CA, May 2001.

- HVAC equipment energy consumption accuracy within +/-10% at the rated conditions (ROM vs. measurement)
- 85% of faults identified are classified correctly (during 3-month demonstration period)
- Simple payback time is less than 5 years<sup>24</sup>
- SIR is greater than 1.25.

## 5. What are the performance results?

The assessment of the major performance objectives is summarized as follows:

- Greater than 20% savings was demonstrated for building energy consumption by improving facility manager decision support to diagnose energy faults and prioritize alternative, energy efficient operation strategies
- A ROM library for building envelope and HVAC equipment has been developed, validated and tested by using demonstration buildings at Naval Station Great Lakes.
- A prototype toolkit to seamlessly and automatically transfer a Building Information Model (BIM) to a Building Energy Model (BEM) has been developed and tested. This dramatically reduced the time to create a BEM (50% time reduction).
- A tool chain for a scalable probabilistic graphical model based energy diagnostics has been established, tested and demonstrated. Greater than 15% energy savings was achieved by correcting AHU economizer faults.
- A ROM based HVAC operation sensitivity study has been implemented and greater than 20% energy savings was identified by pre-cooling/preheating the building, resetting chilled water supply temperature setpoints, resetting zone temperature setpoints, and optimizing outside air flow rate in the demonstration buildings.
- A visualization dashboard for building performance energy monitoring, HVAC operation strategies prioritization and energy diagnostics has been developed and deployed in demonstration buildings at Naval Station Great Lakes. This dashboard provides an effective way for building facility managers to perform building performance decision-making.
- Faults and issues identified by the advanced building energy management system were valued by the facility team because the tool provided additional visibility into the building operation that was not provided by the existing traditional building management system. This additional information allowed the facility team to identify previously unknown operational issues and prioritize their maintenance actions

## 6. What are the findings and recommendations?

By using scalable probabilistic graphic model based FDD algorithms, the following faults were detected and diagnosed from the demonstrated sites: Building 7230 (Drill Hall) and Building 7113/7114.

- Economizer faults: Approximately 2,000 CFM more outside air intake during non-economizer modes (Building 7230)
- Lighting faults: lights on during unoccupied hours (Building 7230)
- Economizer faults: The control sequence of operation was incorrect due to errors in the enthalpy calculations. This caused significantly more outside air intake during hot summer days (e.g., 100% vs. minimal outside air intake) (Building 7113/7114).

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<sup>24</sup> DoD Energy Managers Handbook <http://www.wbdg.org/ccb/DOD/DOD4/dodemhb.pdf>

- Economizer faults: Outside air fraction was not minimal in the heating mode (Building 7113/7114).
- Absorption chiller issues: Chiller 1 was turned off due to operational issues during the whole demonstration period. Chiller 2 had issues related to a leaky steam pipe and, steam valve oscillation. Chilled water temperature setpoints could not be maintained during hot summer days, consequently, the AHU supply temperature setpoints and room temperature setpoints could not be maintained ( Building 7113/7114)

The following HVAC operation strategies were evaluated by using ROM based integrated building model:

- Pre-cooling and pre-heating (Building 7230).
- Chilled water supply temperature setpoint reset (Building 7230).
- Zone temperature setpoint reset (Building 7113/7114).
- Out air fraction optimal control (Building 7113/7114).

### **7. What should DoD consider when implementing the technology?**

During the demonstration process at Naval Station Great Lakes, the maturity of the different technology elements have been assessed with gaps identified that impact the successful deployment of a building energy performance monitoring and diagnostics system. After the completion of the Naval Station Great Lakes demonstration, it is recommended that the following list of activities should occur to ensure widespread technology deployment at the DoD.

- Develop low cost and scalable building energy monitoring systems.
- Implement a robust and scalable middleware for DoD buildings.
- Deploy a secured DoD network for energy efficient buildings.
- Integrate Energy Human Machine Interface (eHMI) applications for DoD building facility operations.
- Implement a scalable process for DoD building data collection.

### **8. What products are on the market or will emerge soon?**

During the demonstration, the UTC stage-gated technology and product development processes have been applied to begin to transition the technology into a commercial product. The advanced building energy management system can be a part of a new BMS product or can be applied as an overlay on an existing BMS. To support a large-scale DoD deployment, UTRC has been engaging expertise from UTC businesses:

- Automated Logic Corporation (ALC) – The demonstrated technology elements including BMS integration (middleware), energy diagnostics, and HVAC operation sensitivity analysis can be integrated into the ALC WebCTRL BMS.
- NORESKO provides energy services to DoD facilities worldwide.

### **9. How much will the technology cost in terms of time, people and money to install, operate and maintain?**

The table below provides the high level summary for cost structure using Building 7113/7114 as an example to deploy the proposed aBEMS.

<b>Cost Element</b>	<b>Estimated Costs (\$)</b>
<b>Hardware capital costs</b>	\$70,919
<b>Installation costs</b>	\$79,210
<b>Consumables</b>	N/A
<b>Facility operational costs</b>	N/A
<b>Maintenance</b>	One day per year (\$1000)
<b>Hardware lifetime</b>	0
<b>Operator training</b>	One day (\$1,000)

**10. What policies and standards should DoD adjust to improve adoption of the technology?**

The DoD should begin to publish guidelines and standards in the following areas to facilitate the deployment of advanced building energy management systems across DoD buildings and facilities:

- A design guideline to determine the minimum set of sensors/meters required to deploy a comprehensive energy monitoring system for both new construction and retrofit of existing buildings. This guideline should include a check list of sensors/meters and decision flow charts for different HVAC systems.
- A guideline to establish a secured and integrated DoD network for building applications.
- A standard to share building energy usage data via a secured network using native communication protocols such as BACnet and LonWorks etc.
- A standardized process to automatically collect building information from available references and transfer them to building energy applications such as building energy models.